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DEFENSE OF NORTH AMERICA

Final Report

of

Project Lamp Light

15 MARCH 1955

VOLUME I

of 4 volumes

N5-ORI-078 TASK ORDER 90

MASSACHUSETTS INSTITUTE OF TECHNOLOGY

SECRET

This document consists of 224 pages, 750 copies.

Massachusetts Institute of Technology

Defense of North America

Final Report

of

Project Lamp Light

15 March 1955

Volume I

of 4 volumes

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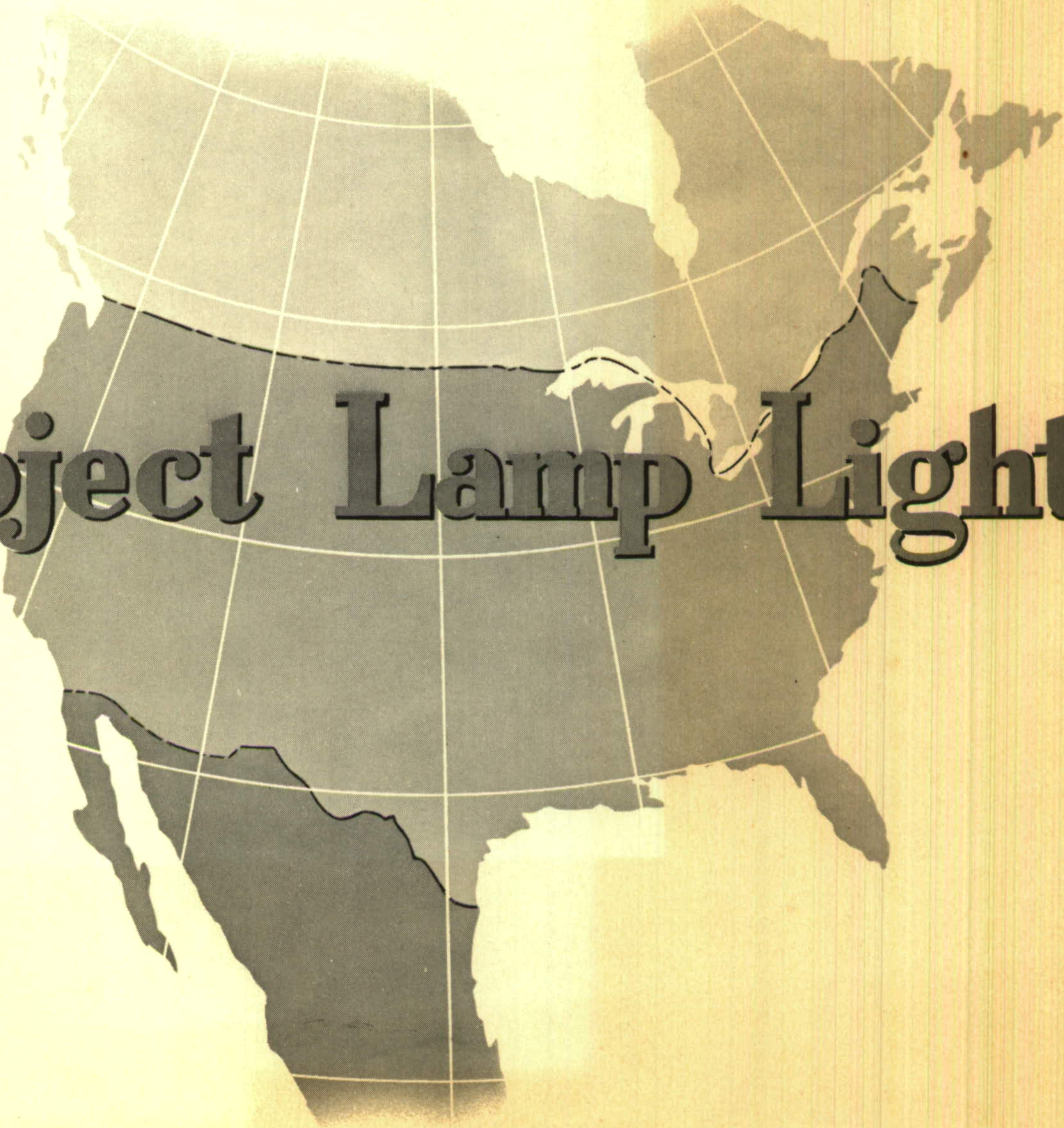

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"FOREWORD"

The structure of this report is patterned after the organization of Project Lamp Light. The work of the Project was carried on in a number of groups, each studying a particular aspect of the total problem. The membership of each group is shown at the end of this foreword. There was strong interaction, both planned and informal, between these groups. Information from the Component Groups was used by the Systems Groups in their design studies, which in turn led to new specifications for components. In the Evaluation Group, an attempt was made to analyze and appraise the over-all result by qualitative and quantitative methods.

Chapter 1 is designed as a brief summary of the entire report. Here the reader is addressed by the Project as a whole. We have tried to be short and readable in stating our main conclusions; the details, the supporting evidence and the necessary qualifications are developed later in the report.

Chapters 2, 3 and 4 deal with radar problems and represent the activities of the Radar Group. Doppler detection systems are separately treated in Chapter 5. In Chapter 6 the Communications Group has summarized its studies. Chapter 7 reviews the work of the Data Processing Group. Chapter 8 deals with identification problems. Defense against electronic countermeasures, discussed in Chapter 9, was the field of work of the Counter-Countermeasures Group. Chapter 10 reviews the studies of the Aircraft and Weapons Groups.

Following these component chapters, the report takes up the systems studies of Project Lamp Light. Chapter 11, on Design Objectives, and Chapter 15, on Systems Evaluation, were prepared by the Evaluation Group. Systems design studies were pursued by two major groups: the first, Air Defense Systems, concentrated its efforts on the contiguous defense zone, and prepared the material assembled in Chapter 12; the second, Early Information and Sea Threat, investigated the problems of the remote zone (Chapter 13) and the defense against the seaborne threat (Chapter 14).

A final chapter, prepared by the Navy Project Officer, deals with the history, organization, and operation of Project Lamp Light.

Most chapters are supplemented by appendices in which particular subjects are further developed by individual members of the Project. These monographs, in general, represent the efforts and conclusions of individuals, expressed in their own language, whereas the chapters themselves are the results of group collaboration.

The report as a whole was prepared more rapidly than high editorial standards would permit. The governing consideration has been the urgency of placing the results of the project into the hands of the armed services.

PROJECT LAMP LIGHT

MASSACHUSETTS INSTITUTE OF TECHNOLOGY

J. R. Killian, Jr. President

E. L. Cochrane *Vice-President for Industrial and Governmental Relations*

J. R. Zacharias *Technical Director, Project Lamp Light*

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Summary

INTRODUCTION

Air defense is a major element of our national security. The Soviet atomic explosion of 1949 and the wars in Korea and Indochina have created insistent demands that we improve the protection of our strategic air bases and urban centers against air attack. Evidence of Soviet progress in thermonuclear weapons and long-range jet aircraft has highlighted the urgency of the situation.

Advances in our air defense system have been made in several important directions. The aircraft control and warning net has been expanded and modernized; identification procedures have been tightened; we have more interceptor squadrons equipped with better aircraft and more lethal weapons; local defenses have been strengthened. The Continental Air Defense Command's program looks to the further systematic improvement of these capabilities.

The main problem now before us is the outward extension of this system. The best air defense would be the complete destruction of the enemy's aircraft on their home bases prior to takeoff. Since we cannot hope to achieve this, we must create a defense system of such depth that early warning is given of approaching hostile bombers, that they are continually harrassed during their approach, and that they are intercepted and destroyed before they reach their targets in North America.

Outward extension of the existing defenses is required with particular urgency for the ocean approaches to our important cities on the Atlantic and Pacific Coasts. A precision data zone suitable for intercept control is to be established with radars on Texas Towers, picket ships, and AEW aircraft. This contiguous zone, several hundred miles in depth, must be designed as an extension of the continental SAGE System. The compatibility of the continental

Summary

system with the naval forces extending it seaward, and the related mechanization of data handling, were the specific problems that led to the formation of Project Lamp Light. Communications are a crucial factor in the solution of these problems.

Outside the contiguous data zone, a somewhat different type of surveillance is obtainable from merchant shipping. While not suitable for interceptor control, properly coordinated information from this source would be extremely valuable.

To obtain the earliest possible indication of air attack, early-information lines are required in addition to general surveillance. The first distant line of this type is the DEW Line in the Far North, scheduled for operation in 1957. Plans are under study to extend this line by surface stations on land, ice and sea, and by AEW aircraft.

The information obtained by these techniques in the remote zone is different in kind from the precision data cover provided in the contiguous zone or over fleet units. Interception and combat in the remote zone would require interceptor aircraft of very long range, equipped with large search radars. Guided only by the early-information net, these aircraft would take off from distant bases, use their own radars to find the enemy, and attack with long-range air-to-air missiles.

The air threat to our national security is paralleled by a seaborne threat directed against our coastal targets and lines of communication. Information to counter this threat is derived from the systematic surveillance of surface traffic as well as from submarine-detection systems. We must find techniques of combining air and sea surveillance functions in naval operations wherever this can be done without sacrificing good performance.

Summary

Within the general problem area that has been outlined here, Project Lamp Light has studied component technology as well as complete systems.

Defense against intercontinental ballistic missiles has not been considered by Lamp Light; this important problem is currently in the hands of a special committee of the USAF Scientific Advisory Board. Nor have we studied the enemy's possible use of nuclear propulsion for his aircraft, since it is unlikely to change our general method of defense for the period 1955-1960.

AEW RADAR (see chapter 2)

OCEAN AREAS

To extend our defense perimeter outward over the sea and into the arctic, we must learn to use aircraft as platforms for large search radars. The AEW missions of today are severely limited by clutter whenever the sea is rough; we urgently need better radars for our ocean patrols. Larger antennas, higher power output, and a more judicious choice of frequency will help. By using interim conversions, we can improve the performance of search radars and height finders within the next few years. A parallel long-term program will enable us, between 1958 and 1960, to install high-power radars of advanced design on search aircraft carrying 30-foot antennas. Over the sea, we shall then have reliable search ranges of 200 miles on medium jet bombers at all altitudes.

LAND AREAS

Over land, the radar search problem is much more difficult. No complete solution of the clutter problem is in sight at present. We need, first of all, reliable measurements of land clutter over northern Canada, Greenland, and the polar ice fields. We can then embark on a determined research and development effort toward the equipment we badly need for AEW operations over those regions.

Summary

HEIGHT FINDERS

To obtain height data on all targets within the AEW search range, we must keep height-finder improvement in step with the search-radar program. In the search aircraft of 1960, a UHF search radar can be teamed up with an S-band stacked-beam radar to provide simultaneous search on two frequencies as well as height information.

AI RADAR (see chapter 3)

AI radar is the crucial element of the air defense battle during that brief interval in which the interceptor must position itself for weapon release with higher precision than ground control can provide. For rocket armament, this calls for lock-on ranges of 10 miles; for missile armament, 15. At altitudes below 5000 feet, existing radars fall far short of these ranges. The resulting low-altitude gap is one of the outstanding defects of our air defense system; research and development to close it must be regarded as imperative.

The only available interim solution is the APG-43 continuous-wave radar; maximum effort is justified to have this set in operation soon. Ultimately, we need S-band radars with antenna apertures larger than 40 inches. Pulse-Doppler systems look promising and deserve full exploration.

SURFACE-TO-AIR RADARS (see chapter 4)

The large ground- and ship-based search radars which will provide most of the data for the air defense battle can be expected to perform well, so well indeed that the enemy will try to blind them by jamming. In this he will easily succeed. We must make it far more difficult for him in the future. By using a wide diversity of frequencies, we can compel the enemy to carry a large complex of jammers and to spread the available power over a wide spectrum. Having thus reduced the effective jamming power against each radar, we can build radars of extreme power and large antenna size which retain limited

capability even in the presence of jamming. Finally, we must develop techniques for correlating azimuth and height information from different sites so that we can determine the position of the jammers after radar echo ranging becomes impossible.

FLUTTAR DETECTION SYSTEMS (see chapter 5)

Fluttar is a system for the detection of moving targets that cross a line between a transmitter and a receiver geographically separated from each other. Such a system provides information complementary to that derived from radar. The two systems can be combined into an excellent data source for target detection, flight evaluation, and complete early-information cover.

Fluttar yields characteristic visual and aural target records - "Fluttar-prints" - by which different aircraft may be distinguished and a flight of two or more aircraft recognized. Used with radar on early-information lines, Fluttar can add low cover and target recognition and be particularly helpful in bridging difficult water gaps such as the Davis Strait.

COMMUNICATIONS (see chapter 6)

REQUIRED LINKS

Reliable communications are a vital factor in adequate air defense. They are needed between air and ground, both within and beyond the line-of-sight. They are needed from ship to ship and between ships and shore stations. They are needed as point-to-point relays between different ground stations.

The data-processing systems proposed for fleet units engaged in air defense or antisubmarine operations impose special demands on communications. The facilities now available to the fleet cannot properly meet these demands.

Summary

NEW TECHNIQUES

By proper application of new techniques and better utilization of existing facilities, we believe all military communications problems can be technically solved, provided that no unreasonable or unnecessary demands are made.

LINE-OF-SIGHT

The capacity of the present short-range communication system is restricted by interference between channels. A new system of multiplexing by means of time-sharing is proposed in this report under the designation Centipede. This system will provide voice and data transmission for a large number of networks on a single radio-frequency channel.

BEYOND-THE-HORIZON

The new scatter modes of propagation such as meteor forward scatter, ionospheric scatter and tropospheric scatter, provide means of solving the beyond-the-horizon transmission problem that are much more reliable than the usual ionosphere-reflected signals.

DATA PROCESSING (see chapter 7)

OBJECTIVES

Modern techniques of data handling and data processing are essential to the Navy's role in continental defense, and offer a major opportunity for increasing the effectiveness of the fleet. The present manual methods of handling data on board ship are slow, inaccurate, and are saturated by a few tracks. Well-designed data processing is the key to greatly increased single-ship capacity, rapid exchange of data among ships in a fleet, and compatibility with the shore system.

TIME SCALE

We therefore believe that the U. S. Navy should have a modern data-processing system at the earliest possible time. Because it will take more than two years to get a high-performance digital system, we are forced to conclude that two systems must be programed:

Summary

Phase 1: An analogue system for installation beginning in 1957;

Phase 2: A digital system for installation as soon as it can be developed and produced, and not later than 1960.

EDS AND DATAR

For Phase 1, the Electronic Data System (EDS) designed at the Naval Research Laboratory meets the most important interim requirements in the fleet and in sea picket ships assigned to continental defense.

For Phase 2, the Canadian Datar System is, in our opinion, the best starting point for a research, development, and production program aimed at 1960 delivery of high-performance digital data-processing systems.

RESEARCH

A continuing program of research is needed to determine the relative advantages of general-purpose computers, special-purpose computers, and combinations of both, for data processing in the fleet.

RELATED EQUIPMENT

Air defense information from picket ships is to be transmitted to a shore station equipped, initially, with a commercially available general-purpose computer, later with modified SAGE equipment.

Together with related data-processing equipment in AEW aircraft and with suitable communication links, this program will provide capacity, speed, and flexibility commensurate with the input detection devices and the weapons that are likely to be available.

Summary

IDENTIFICATION (see chapter 8)

FAIL-SAFE IFF

Atomic weapons have given a new importance to the problem of identifying friendly and hostile aircraft. We must face up to the need for a reliable IFF system, a system that makes it impossible for an enemy bomber to appear as a friendly aircraft. The system must fail-safe: the lives of one million civilians cannot be jeopardized to save one pilot whose equipment is defective.

COLD WAR IFF

In the cold war period, adequate procedural identification can be achieved by the gradual improvement of navigation, discipline, and the installation of CAA safety beacons.

HOT WAR IFF

In a hot war, it is vital to have secure electronic IFF in addition to procedural identification. Our present Mark X IFF and its SIF modification are not secure and are therefore dangerous. An insecure IFF system is worse than none. A secure system is feasible; its secret element must be the code key, not the equipment. The development of such a system is a matter of high urgency.

ALLIED AIRCRAFT

It is essential to our defense that U. S. and allied aircraft use the same IFF system. This can be done without risk of compromise if we rely on code secrecy rather than equipment secrecy.

PRIORITIES

IFF development has been hampered by unwarranted confusion between IFF and beacon functions. The most urgent problem is to prevent hostile bombers from masquerading as our own aircraft. We shall also want to protect friendly aircraft from unauthorized interrogation, but this is a secondary objective.

Summary

DEFENSE AGAINST ELECTRONIC COUNTERMEASURES (see chapter 9)

ECM THREAT

An enemy determined to paralyze our air defense will concentrate his efforts on the electronic devices that constitute its nerve system. His megaton bombs make it easy for him to assign a large fraction of an invading bomber force to the task of disabling our radars and our communications. He can limit our radars to one-tenth of their normal range. He can mislead us concerning the size of his raid. He can cause our radars to report so many spurious targets that the data-handling system will be saturated. He can jam our communications and navigation systems so that interceptors will have no guidance outside the range of their own AI sets. He can interfere with the control and fuzing of our missiles.

COUNTER-ECM

To prevent a catastrophic breakdown of our defenses, we must train our men to operate in the face of intensive countermeasures, we must protect ourselves by frequency diversity and extreme power, and we must adopt numerous specific techniques designed to reduce, by their cumulative action, the vulnerability of our radars, our communications, and our weapons. We can never afford to lose sight of the fact that the enemy's electronic countermeasures are his cheapest weapon against our air defense system.

HULT NOTE

ELECTRONIC WARFARE

It is doubtful whether we can improve our radars and communications to the point where the enemy will find it wholly useless to attack with countermeasures. But we can and must learn to use the radiation from an airborne jammer to bring about the destruction of its carrier. This calls for passive ground techniques for direction finding, homing indicators for interceptors, and, above all, missiles that home on jammers. If by vigorous exploitation of these means we

Summary

can convince the enemy that jamming radiations are a more serious danger to him than to us, we shall have gained the upper hand in the electronic war.

AIRCRAFT AND WEAPONS (see chapter 10)

AIR-TO-AIR MISSILES

Provision of air-to-air missiles with small nuclear warheads (a few kilotons' yield) in ample supply and considerable variety of guidance, range and size seems the only simple method of preventing raids of unfortunate compactness, and raids that fly at extremes of height and speed. Such nuclear-warhead weapons must have jump-up capability and speed to enable the launching interceptor to make a reasonably safe attack. No other known type of air-to-air weapon can be expected to be a satisfactory substitute for them. The quantity of small nuclear warheads that are required (numbered in the thousands) seems to be in every way reasonable.

Air-to-air homing or guided missiles must make up for the inability of an interceptor to maneuver at the heights and speeds required for the interception of bombers. This ability must be reflected in their speed, range, jump-up capability and in their control. The closing phase of a homing missile's course is far less susceptible to countermeasures or evasion than almost any other part of the total air defense system. The easiest point of view to adopt is that the interceptor is a missile launching platform with modest capability.

SURFACE-TO-AIR MISSILES

The major gap in the present planning for surface-to-air missiles lies in their inability to attack fast, high- or low-altitude, air-to-surface missiles. A careful systems study of the detection, acquisition, tracking and control problems is required. It has not been possible to include this in Project Lamp Light.

Summary

MISSILES THAT HOME ON JAMMERS

The lack of a weapons system that exploits jamming transmissions by enemy bombers is one of the most important gaps in the present U.S. air defense plans. It seems possible to determine the time appropriate to launch an air-to-air homing missile by range determinations that involve only passive observations. Once launched, a missile that seeks its prey by purely passive measures seems difficult to jam or evade, provided the aircraft carrying the jammers are separated by a few miles, as they would be if some of the interceptor weapons available were atomic-warhead types. We seek conviction on the part of an enemy pilot that his jamming transmitter is the beacon that assists him in his own destruction.

SYSTEMS DESIGN OBJECTIVES (see chapter II)

BASIC DEFENSE CONCEPT

The Lamp Light Study has been governed by the general concept of national defense enunciated by responsible officials of the United States. Under this concept, we rely for defense basically and primarily on the deterrent effects of a long-range air force, designed to exploit the power of nuclear weapons, and of a strong tactical air force, also equipped with nuclear weapons and deployed according to plans for a common defense of the entire western world.

AIR DEFENSE FORCE

A third force, based on and around North America in accordance with a joint United States-Canadian plan, is designed for defense and consists primarily of local defense weapons, manned and unmanned interceptors, and electronic facilities.

The outward extension of this air defense force has been the principal subject of Project Lamp Light. This problem involves the design of the air defense system as a whole, and the analysis of modifications intended to improve its performance.

Summary

AIR THREAT

The first consideration in designing an air defense system is the threat against which the system is intended to protect our country. We have assumed that before 1960 the Soviet Union will be capable of staging an all-out massive air attack against North America. We consider such an attack more dangerous than the sneak attack in which a few aircraft penetrate the air defense system. We visualize TU-4, Type 39, and Type 37 aircraft in the quantities discussed in the National Intelligence Estimates. While we must be prepared for invasion at altitudes up to 60,000 feet, we cannot dismiss the threat of low-altitude penetration. By 1960, we believe a 100-mile air-to-surface missile will be available to the enemy. We have assumed that weapons of megaton yield would be used in such an attack and that the bomb carriers would be accompanied by similar aircraft capable of intensive electronic countermeasure activity. We have given much attention to the simultaneous threat of large numbers of short- and long-range decoys. Lastly, we have considered the possibility that this entire air attack might be synchronized with the launching of guided missiles from enemy submarines and surface ships.

LEVEL OF DEFENSE

The objective of defense system design is to provide a level of protection adequate to this threat. This does not mean that the system will provide complete and absolute protection; it does mean, however, that the system will not collapse when faced with the assumed maximum threat. Such a system will not prevent hardship and injury to our country, but it will preserve our existence as a nation.

COST OF DEFENSE

We believe that an air defense system providing this level of defense is possible within budgets of the approximate magnitude proposed by the Air Defense Command for the 1955-1960 period. Systems design and evaluation were made within a narrow range of values around this level.

Summary

THE CONTIGUOUS AIR DEFENSE ZONE (see chapter 12)

THE LAMPLIGHT MODIFICATION

In exploring the possibilities of achieving more effective continental defenses than present plans will provide for 1960, Project Lamp Light was led to the design of a modified air defense system. This design calls for only moderate changes in the quantities and deployment of the facilities and weapons now contemplated by the Air Defense Command in ADR 54-60.

COMBAT DEPTH

The outstanding feature of the Lamp Light system is a widening of the contiguous surveillance data zone around the defended areas. We propose that this zone extend out to 1400 miles for high-altitude targets, and 1000 miles for low-altitude targets. In this way, we shall widen the combat zone to about 700 miles, and thus make more effective use of the combat ranges of the interceptors that we shall have in operation by 1960.

before '60?

Such a system will make it more difficult for the enemy to use saturation tactics against a narrow sector of our defenses. It will give us more time to break up large compact formations by continuous attack, and to destroy bombers before they launch decoys and air-to-surface missiles.

OCEAN APPROACHES

The necessary data over the ocean approaches are best obtained by a combination of AEW aircraft and picket ships. These vehicles are to be equipped for the detection and identification of aircraft, surface ships and submarines. They must be able to control air interception and thus provide combat control beyond the coverage of the SAGE System. Data-processing equipment and picket ships must allow efficient interchange of information from shore stations, AEW aircraft, and other fleet units.

Summary

VERY HIGH & VERY LOW ALTITUDES

The most serious problems in air defense system design occur at very high and very low altitudes. Against targets at 60,000 and 80,000 feet we shall need improved high-altitude missiles and air-to-air missiles with jump-up capability. Against low-altitude targets, including fast air-to-surface missiles launched from enemy bombers, we need effective surface-to-air defense missiles.

THE REMOTE AIR DEFENSE ZONE (see chapter 13)

The region that extends from the perimeter of the contiguous air defense zone to the territory controlled by the Soviet Union has been studied with two objectives in mind: (a) securing early information; (b) extending the area of possible combat operations.

EARLY INFORMATION

In remote regions, even a moderate degree of surveillance will deny to the enemy any large chance of proceeding far on his mission without coming under observation. To our own forces, the additional warning time that may be derived from early information is a major advantage.

METHODS

Two different methods are available for aircraft surveillance in a remote zone: (a) planned barriers (lines), so placed that even a single aircraft is likely to be detected upon crossing; (b) general surveillance extending over broad areas in which so many detectors are deployed that an enemy aircraft is unlikely to avoid them all.

BARRIERS

Sea-wing extensions by AEW aircraft and picket ships between Hawaii and Kodiak, and between Newfoundland and the Azores, will prevent end runs around the programmed DEW Line from Alaska to Baffin Island.

Better coverage and reliability can be obtained later by replacing some of these

Summary

patrols with land-based detection stations in the Aleutians, in western Alaska, and in Baffin Island, Greenland and Iceland. Between 1958 and 1960, these facilities can be combined into a continuous barrier from Midway to the United Kingdom.

An important opportunity to acquire distant information can be exploited in the near future by installing alarm radars at the Joint Canadian – U.S. Weather Stations in the Queen Elizabeth Islands.

GENERAL SURVEILLANCE

In the ocean approaches to North America, friendly naval vessels and merchant ships can provide the basis for a general surveillance radar system that offers high effectiveness at relatively low cost. The system is available today, requiring only the installation of suitable radars and the organization of a reporting net. A similar system might be created by providing radars to inhabited outposts in northern Canada.

REMOTE AIR BATTLE

A long-range interceptor weapon system and its associated radar and air-to-air missiles are technically feasible and can be developed by 1961-1962. The distance from the heartland at which interceptions can be made can be extended from about 700 to over 2000 miles. If employed in remote air battle missions, this weapons system will be an important deterrent to the Soviet striking force.

AIRCRAFT

For earliest operational use, the B-47E can be modified to carry a large antenna and the necessary missiles. For later introduction, the B-58 or PGM-1 can be modified, or a new high-speed long-range interceptor designed.

Summary

DEVELOPMENT PROGRAM

If we start at once to develop suitable weapons, radar and aircraft, we can be ready for the remote air battle if future decisions demand that capability. Meanwhile, we can study the tactics and the alterations required in the rules of engagement.

DEFENSE AGAINST THE SEABORNE THREAT (see chapter 14)

North America is open to attack not only by aircraft but also by ships and submarines. Airborne missiles with nuclear warheads can be launched from the surface of the ocean several hundred miles off our coasts. Our ports can be destroyed by nuclear mines. The air defense system itself can be crippled by seaborne attack on picket ships.

OCEAN SURVEILLANCE

Defense against this threat requires an ocean surveillance system which detects, identifies and tracks all vessels on and below the surface of the sea. We propose the establishment of 600-mile-wide contiguous surveillance zones off our coasts, supported by remote surveillance lines to provide early information. The existence of such a system will be a strong deterrent, even before its technical performance becomes wholly satisfactory.

CENTRALIZED DATA PROCESSING

We visualize the use of digital computers at a Sea Surveillance Center where data from radars, radio direction finders, and underwater sound detectors are correlated with sail plans, ships' reports, and tables of ships' characteristics. The resulting information on position, course, speed, and identity of all vessels is displayed in a summary plot for command purposes.

IMPROVED DATA SOURCES

Such a system will become fully effective only if we continue to improve the available data sources. Experimental work is needed on shore-based ground-wave radar at about 2 Mcps. For improved underwater detection, we need better hydrographic

Summary

data, particularly in northern waters. In addition to improved passive sonic detectors, we need a long-range, low-frequency, active system to meet the threat of the silent submarine.

AIR DEFENSE SYSTEMS AND THEIR EVALUATION (see chapter 15)

MAP EXERCISES

The systems proposals of Project Lamp Light were subjected to evaluation by map exercises and by mathematical procedures. The simplest method of visualizing a system's effectiveness against an attack, and a good method of estimating its quality, is to take the position of an enemy and plan an operation against it, and then study the possible actions of the defense against the attack as it progresses step by step across a map. Two important conclusions emerged from such map exercises:

SAC DEFENSE

Both the ADR 54-60 System and the Lamp Light Modification satisfy the warning and defense needs of the Strategic Air Command. If plans for speedier evacuation, increased readiness, and further dispersal are implemented, the defenses will adequately protect SAC's retaliatory strength.

MASS ATTACK

Against strong air defense systems, a concentrated mass attack is best from the enemy's point of view and is therefore the most important type of attack to consider in air defense evaluation.

MATHEMATICAL EVALUATION

Mathematical procedures were used for an approximate quantitative assessment of the Lamp Light and ADR 54-60 systems. Urban population centers in the United States were assumed to be targets, and calculations were made to estimate the number of enemy bombers that must enter the defense system

Summary

to produce 15 million deaths from bombs on target. This number of hostile aircraft was taken as an index of the effectiveness of the defense system. Separate calculations were made for systems representing different cost levels, for different types of systems, and for different assumptions regarding the use of decoys and anti-air-to-surface missiles.

From the graphs in Chapter 15 which show the results of these calculations, we have drawn the following major conclusions:

(1) Lamp Light Modification

The modified air defense system proposed by Lamp Light for 1960 will provide somewhat better defense, at a comparable cost level, than the system proposed in ADR 54-60.

(2) Decoys

The use of decoys by the enemy could double the effectiveness of his attack against our air defense system.

(3) Anti-ASM Missiles

Conversely, a capability in our air defense systems against the enemy's air-to-surface missiles could double the effectiveness of our air defense system against his attack.

(4) Remote Air Battle

Quantitative comparisons of 1960 air defense systems with remote air battle capability vs systems of equal cost in which all combat resources are concentrated in the contiguous zone, show no great disparity in combat effectiveness between the two types of systems. Qualitative arguments, particularly on the ground of its deterrent value, indicate that a remote air battle capability would improve the air defense of North America.

CHAPTER 2

AIRBORNE EARLY-WARNING AND CONTROL RADARS

CHAPTER 2

AIRBORNE EARLY-WARNING AND CONTROL RADARS

INTRODUCTION

For some years the U.S. Navy and U.S. Air Force have been interested in the development of airborne search radars; aircraft equipped with such radars are now about to enter into operational use. Considerable emphasis is being placed on the use of airborne early-warning and control (AEW&C) radars, and demands are being made on them that cannot be fulfilled by the existing equipment. In this chapter, the requirements imposed on the radars by the defense systems is examined, and an attempt is made to evaluate the performance of the radars that are now being used in the WV-2 and RC-121 aircraft.

The threat against which the AEW aircraft is to be used is variable over wide limits. The Russians have available type TU-4 piston-driven medium bombers, type 39 medium jet bombers and type 37 heavy jet bombers. In Table 2-I, data are given on the speed, range and ceiling of the various aircraft types. Since B-47 medium bombers can fly the last 1500 miles of a 3000-mile mission at an altitude as low as 500 feet, it is necessary to assume that enemy bombers may arrive at North American defense lines at any altitude from 500 feet up to their terminal ceilings.

TABLE 2-I

CAPABILITIES OF RUSSIAN BOMBERS

Aircraft (bombers)	Maximum Speed (knots)	Maximum Altitude (ft)	Combat Ceiling (ft)	Terminal Ceiling (ft)
Medium (piston)	350	30,000	36,500	42,000
Medium (piston, mod.)	360	30,000	37,500	42,000
Medium (jet)	550	42,000	43,500	49,700
Heavy (jet)	550	45,500	48,000	56,300

In the Lamp Light study, it was assumed either that a sneak attack followed by a mass attack might be made, or that the first warning might be a mass attack. A mass attack is assumed to comprise about 1000 bombers which it is argued would be mostly piston-driven in 1957 and mostly jet-propelled in 1960. The consensus at Lamp Light is that the bombers may arrive within the defense lines either at their ceilings so as to fly over the interceptors, or at an altitude of 500 feet in order to postpone radar detection; in either case, it is assumed that 1000 bombers would approach along a front 50 miles wide by about 250 miles deep.

For later discussion, a standard radar cross section is needed that can be used to characterize the targets presented by the individual bombers in the enemy fleet. It is commonly assumed that the radar cross section of the TU-4 is the same as that of the B-29 – namely, 8 square meters – and that the Russian jet bombers present the same cross sections as the B-47 – that is, 2 square meters; since the latter is the smaller, it is chosen as the characteristic value. A few comments on the radar cross section of the B-47 are needed to justify the choice of this small area. A plot of radar cross section against azimuth is a curve that consists of a few major peaks as great as some hundreds of square meters and many minor residual lobes. The target cross section of 2 m^2 is an average associated with the residual lobes.

wP5?

On the map in Fig. 2-1 are drawn, in approximate location, the twelve AEW lines that have been considered at Project Lamp Light. The location of these lines is important because the nature of the terrain is one of the factors that determines the magnitude and the spectral width of the clutter that is returned to the radar. Lines 1, 2, 3, 4, 5, 6 and 12 pass largely over the sea, which for design purposes must be considered to be very rough; these lines are expected to provide cover from the sea surface to approximately 60,000 feet. In addition to detection, Lines 1, 2, 4 and 5 are required to supply data to the SAGE System which will permit an interception to be guided. Lines 3 and 6 are for contiguous early warning only.

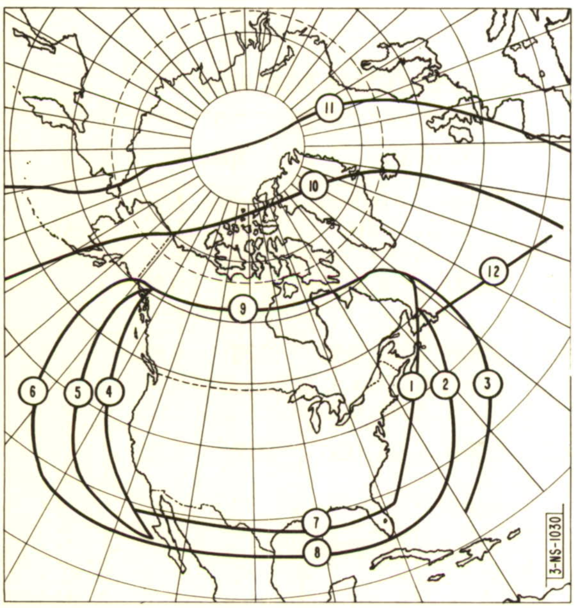


Fig.2-1. AEW lines considered by Project Lamp Light.

Lines 7 and 8 pass partly over sea and partly over land, while Line 9 passes wholly over land; not much can be said about the land surface in all three cases except that it is very varied and in places mountainous. The data and coverage required from Line 7 are the same as that from Lines 1, 2, 5 and 6, but low-resolution data can be tolerated from the radars in Line 8. Low-resolution data and high-altitude cover only can be tolerated from the radars in Line 9, although the point has been made by the Project's systems groups that an undesirable low-altitude hole will then exist.

Lines 10 and 11 pass over the sea and also over ice mountains and the polar ice fields. The defense system has been planned so that early-warning information only is required from them.

The aircraft chosen by the Navy and Air Force for AEW experiments is the Lockheed Super Constellation (Navy type WV-2; Air Force type RC-121); it carries a 17 × 4 foot search antenna which rotates at 6 rpm in a radome below the fuselage, and a 7 × 2 foot height-finding antenna mounted in a radome above the body of the aircraft. Lockheed has proposed that the aircraft be modified to carry a 37.5 × 7.5 foot radome planned to rotate on a pedestal mounted above the fuselage. This radome would accommodate a 30 × 7.2 foot antenna, and accommodation could be provided for the height-finding antenna in the pedestal itself. These and other modifications that have been discussed are outlined in Table 2-II.

TABLE 2-II

PROPOSED MODIFICATIONS OF SUPER CONSTELLATIONS FOR AEW

		Antenna Dimensions (ft)			Cruising		Speed	
Period	Type	Main Radome	Search Antenna	Height Finder	Range (n. mi.)	Altitude (ft)	Normal (knots)	Min. (knots)
1955	WV-2 RC-121		17 × 4	APS-45	2600	16,000	220	170
1958 to 1960	CL-257 6A*	37.5 × 7.5	30 × 7.2	APS-45	2200	14,000 to 16,000	220	170
1958 to 1960	CL-257 7(R7V)**	37.5 × 7.5	30 × 7.2	APS-45	2500 to 4600	24,000	237	170
1958 to 1960	CL-257		50 × 8			20,000		

*Subfuselage and height-finder radomes removed, Rotadome added.

**Modified wings added, turboprop engines added.

Note: The Super Constellation with new wings and new engines has been wind-tunnel-tested in model form with antenna as shown; further data are not available.

Sideways-looking antennas, which can be faired into the side of an aircraft or mounted on the back of the fuselage as a dorsal fin, have been investigated at the Lincoln Laboratory and at the Hughes Aircraft Company. Dr. Van Atta of Hughes has submitted

several memos on this subject to Project Lamp Light; in these he speaks of dorsal-fin antennas 60 × 6 feet, and side-mounted antennas of 30 × 3 feet; he suggests that these could be supplemented by rotating antennas mounted in radomes of the type used in the WV-2. It is of considerable importance that either the dorsal fin or the side-mounted antenna could be installed in many of the big commercial airplanes, with little modification to the structure and with little change in the aerodynamic properties of the aircraft.

Officials of Boeing Airplane Company have stated that a 4-foot parabolic antenna can be accommodated in a nose radome mounted on the B-47, or a 5 × 7 foot antenna can be mounted further back behind the first production break in the fuselage. The Cornell Aeronautical Laboratory, Inc. has investigated the B-47 as a vehicle to carry an 8 × 3 foot antenna mounted in a radome above the fuselage and it is believed there that the aircraft could fly at altitudes ranging from 24,000 feet initially to 37,000 feet in the final part of its cruise at a speed of 324 knots. Boeing engineers are investigating the possibility of mounting a 60 × 6 foot sideways-looking, dorsal-fin antenna on the back of the B-47 aircraft.

The radar equipment of the WV-2 aircraft is an APS-20B radar with a 17 × 4 foot antenna and an APS-45 nodding-beam height finder. Flight tests to evaluate these radars have just begun but no results have been published. Freedman and others at Lincoln Laboratory have conducted a series of flight tests to compare the APS-20B radar and a new UHF radar.[1] The trials were well planned and well instrumented but as they say themselves, "It is obvious that more extensive experimentation will be required before firm conclusions can be drawn"; nevertheless, this report contains the best controlled data relative to the APS-20B that has so far been collected.

During the course of these experiments, data were collected on the blip-scan ratios for B-29 and F-89 targets, and on the amplitude of sea clutter and its spectral width. With these data, the Lincoln group was able to extrapolate their results so as to predict the range within which a B-29 target would be visible above the clutter and the noise of the system. Table 2-III and the accompanying comments are taken from Ref. 1.

Four WV-2 aircraft were used in the barrier exercise PACBEX which took place about 250 miles northeast of Oahu in the Hawaiian Islands, 1-3 Dec. 1954. During these two days, one WV-2 was always on-station, executing an oscillating, 50-mile leg at an altitude of 10,000 feet. The targets consisted of naval aircraft of types P2V, AJ, and F3D as well as all commercial aircraft that came within range of the radars. Some comments have been made on the exercise by several observers from Lockheed. From

TABLE 2-III		
EXTRAPOLATED DETECTION OF AN/APS-20B ON A B-29 TARGET		
	Rough Sea Range of Visibility	
Radar Elevation (ft)	Normal (n. mi.)	MTI
5000	60-175	42-175
10,000	100-175	80-175
15,000	130-175	113-175
20,000	163-175	140-175

"Clearly, the AN/APS-20B cannot be operated at 20,000 feet without MTI except on a most marginal basis, since the clutter-to-signal ratio will not exceed one db in the range region indicated (163-175 miles). The addition of MTI is not of great assistance at S-band due to the very wide clutter spectra obtained. Therefore, the additional improvement with MTI still results in a marginal system". (The MTI considered is that obtained with a single delay.)

TABLE 2-IV

RADAR PERFORMANCE, PACBEX TESTS

Sea States 3 to 5

Radar Altitude: 10,000 ft.

APS-45
- Height finder
- Average reliable range: 75 n.mi.
- Target altitudes: 200 to 35,000 ft.

APS-20B
- Search Set
- Sea-clutter circle: 75 to 100 n.mi.
- Maximum range, several detections: 200 to 240 n.mi.
- Minimum range: 25 n.mi.
- Average consistent range: 100 n.mi.

"Most of the targets were detected and tracked through sea clutter."

their memo, the extent of the operation is not clear but they mention that, on the first day, the WV-2 detected 34 aircraft. The comments on the radar equipment are given in Table 2-IV.

In view of the uncertainties in target size and altitude, not a great deal can be said about the relation between the Lincoln and PACBEX results. Detections on high targets at 240 miles with low blip-scan ratios by the APS-20B are not ruled out by the Lincoln results. The average consistent range on large targets is perhaps less than one would expect from the Lincoln data but, since the targets were of all sizes, this probably can be reconciled. It is conceivable that most of the targets that were tracked through clutter were large commercial airliners; if this is not so, the performance of the APS-20B in this respect is much better than was expected by the Lincoln Laboratory group. The reported range of the APS-45 height finder is consistent with its calculated free-space range on a B-29 target.

It is apparent that the radars presently existing in the AEW aircraft do not fulfill future requirements. In the following sections, an analysis is made of the various parameters that affect AEW radar performance – such as wavelength, antenna dimensions, power and pulselength – and of the manner in which these parameters react on the clutter-producing properties of the terrain. This analysis has led to a set of recommendations for the design of certain radars that are considered to be optimum; these recommendations are discussed in the final section of this chapter and details of the designs are given in the appendices.

WAVELENGTH AND ANTENNA SIZE

The requirements placed by Lamp Light on AEW&C radars have been outlined in the introduction to this chapter (a further discussion will be found in Appendix 2-A). With these requirements set forth, it is possible to arrive at some rough specifications for an airborne radar that may be expected to give good performance over the sea. Though the performance over land is difficult to predict and almost certain to be unsatisfactory under some conditions, it is possible to show in what direction certain parameters should be varied to alleviate as much as possible the effects of land clutter.

It is assumed at the outset that the AEW aircraft will fly at about 20,000 feet. Thus the horizon is set at 180 nautical miles. The search radar should be capable of achieving at least this free-space range on the smallest important target, which for the computations made here has been taken as having a 2-m^2 cross section. The radar should

also be competent to see this target against sea and land clutter, and to cover all altitudes from zero to 60,000 feet.

In order to investigate the effect of varying certain parameters, chiefly wavelength and antenna size, the performance of a large number of hypothetical radars was calculated. The methods employed for the calculations are given in detail in Appendix 2-B. For each radar, values of power, pulselength, and other parameters were assigned which were believed to be consistent with components available now or in the near future.

The results of these calculations are best discussed in terms of two different situations: operation over the sea and operation over land.

Operation over the Sea

The nature of sea return has been rather extensively investigated at several frequencies, and it is possible to make predictions of the performance of a radar over the sea with some degree of confidence. The clutter returned from the sea depends on the area illuminated (a function of range, beamwidth, and pulselength), and on the reflectivity of the sea (a function of sea conditions, wavelength and angle of incidence). In general, the angular dependence is so strong that, as the distance from the radar increases, the sea return falls off faster than the return from the target. Thus there will exist a range beyond which the target is free from clutter, and inside which the target is obscured. This clutter-limited range can be greatly reduced by application of single-delay MTI and even further by double-delay MTI. The effectiveness of these procedures depends on the width of the clutter spectrum, which is in turn dependent on the wavelength, antenna size, velocity of the aircraft, and motion of the scatterers.

With a knowledge of these parameters, an inner clutter limit and a free-space range can be calculated for each radar, so that the annulus over which detection can take place can be specified. Curves can be drawn to show, for example, how these limits vary with wavelength, it being understood that variation of wavelength also implies other variations, because a new radar was "designed" for each frequency.

Figure 2-2 shows such a curve for a 17 × 4 foot antenna, which is that presently used in the WV-2. The conditions correspond to flying at 20,000 feet over rough sea. The curve labeled "noise limit" shows how the maximum range varies with wavelength; the two branches represent two possible shapings of the antenna pattern, both of which provide high-altitude coverage. The curve marked "clutter limit" shows the range beyond which the target signal exceeds the clutter. The space between these curves then

represents ranges over which the radar is effective. It is at once evident that at 25 cm and below there is no range over which the radar can detect a 2-m^2 target. By the application of single-delay MTI, the clutter curve can be moved to the position labeled

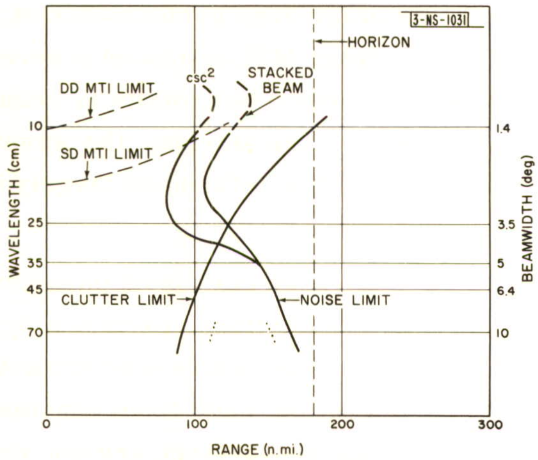


Fig. 2-2. AEW radar performance, 17 × 4 foot antenna, 20,000 feet, over rough sea. For easy comparison, the radars recommended by Project Lamp Light are shown as segments of the curves (dotted).

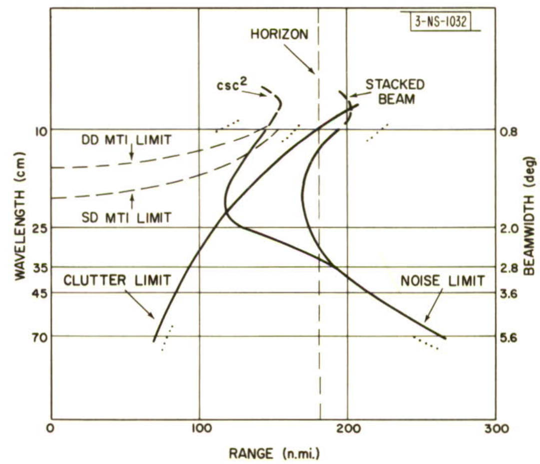


Fig. 2-3. AEW radar performance, 30 × 5 foot antenna, 20,000 feet, over rough sea. For easy comparison, the radars recommended by Project Lamp Light are shown as segments of the curves (dotted).

"SD MTI Limit". Any wavelength above 17 cm now will give clutter-free performance. Double-delay MTI gives further improvement. The range performance of these radars falls somewhat short of the horizon, though by going to 70 cm a calculated range of 160 miles can be achieved.

Figure 2-3 is a similar plot for a 30 × 5 foot antenna. Note that the clutter limits are moved inward, while the free-space range moves out, giving superior performance at all wavelengths. Beamwidths, which are important for resolution, are labeled at the right-hand edge of the plot.

The entire situation can be presented (as in Fig. 2-4) by plotting contours of constant performance using wavelength and antenna size as coordinates. Here the range variation has been omitted and, instead, two demands have been placed on the radar: it must have a maximum range greater than 180 miles, and a cluttered-area radius less than 30 miles. Both these conditions are met if a chosen point lies to the right and above the limit curves shown. Thus, if no MTI is used, the available area lies above the uppermost dotted curve, i.e., wavelengths of roughly 70 cm combined with antennas of roughly 50 feet are required. The application of single-delay MTI moves the clutter

limit downward; now almost any wavelength can be used if the antenna is 30 feet or more, or smaller antennas can be used with the longer wavelengths. The 45° lines show how the beamwidths vary with the choice of antenna and wavelength.

The conclusion to be drawn from this chart is that, if clutter-free performance at high altitudes and over rough seas is to be achieved, single-delay MTI is almost a necessity; and that, if a free-space range of 180 miles with not too large a beamwidth is required, antennas of 30 feet or more should be employed. With this size antenna, the wavelength dependence is not marked, and the choice of wavelength will be influenced largely by the beamwidth that is desired.

It should be noted at this point that, while each of the radars was assigned parameters deemed suited to the components available, some of the assumptions, particularly that of high power and stacked beams at 25 cm, make certain of the radars less attractive from an engineering standpoint, so that the final choice may be made from considerations not exhibited on the diagram, provided that the limits shown there are not violated.

Performance over Land

The discussion of performance over land is necessarily much less specific than for the sea case, because of the almost complete lack of information as to the magnitude of land clutter. The average cross section per unit area, σ_0, which expresses the reflecting power of the ground, has been measured for only a few types of terrain and at the single wavelength of 3 cm. Results from various sources are not in good agreement, giving values of σ_0 varying from −25 to −10 db for conditions presumed to be similar. The available data are given in Appendix 2-B (Fig. 2B-7).

In view of the lack of information as to the value of σ_0 as a function of wavelength, angle and terrain, it was considered impractical to attempt to predict radar performance as was done for the sea case. Instead, a series of diagrams (Figs. 2-5, 2-6, 2-7) was made showing how the clutter-to-target ratio varies with radar parameters for a fixed value of σ_0 taken as 0 db. By adding to the values shown on the diagram any assumed (negative) value of σ_0, one can determine whether, for that particular case, the target signal will be stronger or weaker than the clutter. Thus the diagrams show trends; they will indicate how to make a radar better or worse, but not (in the absence of information about σ_0) whether it is good enough.

The diagrams are all drawn for a range of 100 miles; the clutter-to-target ratios are proportional to range, so that 3 db should be added to all the values for a 200-mile range or subtracted for a 50-mile range.

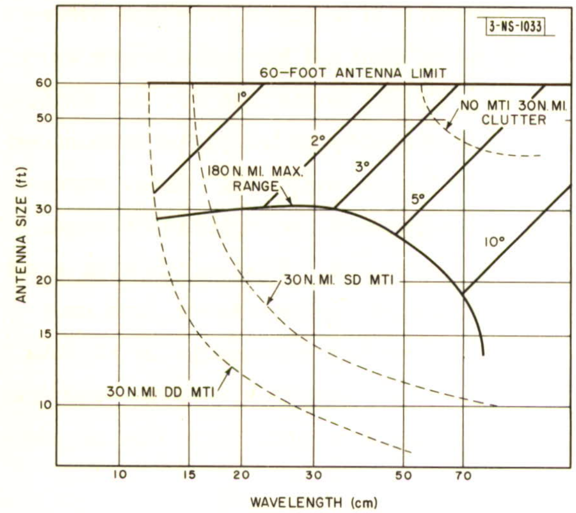


Fig.2-4. AEW radar performance, 20,000 feet, over rough sea, 170 knots.

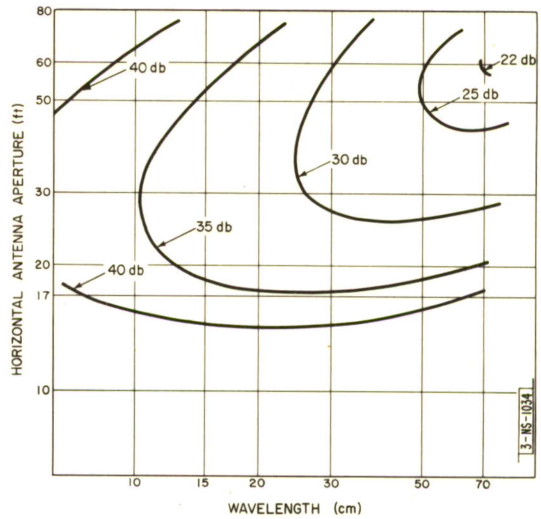


Fig.2-5. AEW clutter-to-target ratio (land). Double-delay MTI; σ_o = 0 db, range = 100 nautical miles.

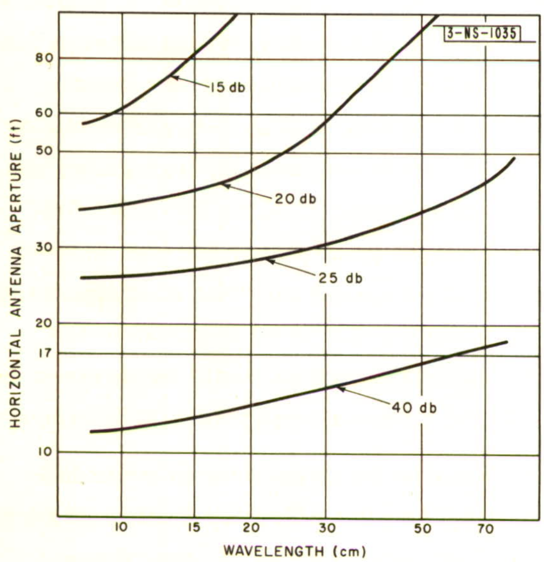


Fig.2-6. AEW clutter-to-target ratio (land). Double-delay MTI with 35-db cancellation limit; step scan to remove scanning clutter; σ_o = 0 db, range = 100 nautical miles.

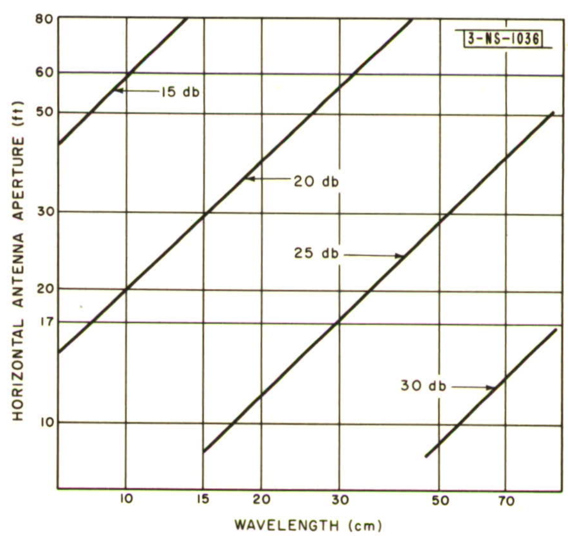


Fig.2-7. AEW clutter-to-target ratio (land). Double-delay MTI with 35-db cancellation limit; step scan to remove scanning clutter and displaced antennas to remove velocity clutter; σ_o = 0 db, range = 100 nautical miles.

Figure 2-5 shows the clutter-to-target ratios as a function of antenna size and wavelength for radars with double-delay MTI. It will be noted that all the values are very high, a result primarily of the assumption $\sigma_o = 0$ db. To get some feel for the situation, a value of $\sigma_o = -30$ db can be assumed. This corresponds to the value measured for scrub pine at 3 cm. Figure 2-5 shows that, under these conditions, radar wavelengths over 30 cm and antenna sizes over 30 feet are indicated, with steady though slow improvement as these values are proportionally increased. Flat earth with sand and grass cover probably has less reflection at the angles of interest here, and one might hope for a limited performance from radars with smaller antennas. A 17-foot antenna would be effective only over those areas whose σ_o is less than −40 db, and the choice of wavelength would make little difference except as it affects (in a way as yet unknown) σ_o itself.

The application of single-delay MTI is very effective in suppressing sea clutter to the necessary degree; in the land case, however, even double-delay MTI does not suffice, and it becomes desirable to inquire whether further action can be taken to reduce the clutter. The failure of MTI to completely cancel the clutter arises from the finite width of the clutter spectrum. This finite spectrum results in part from the scanning motion of the antenna and motion of the aircraft over the ground. The scanning-motion clutter can be largely eliminated by step scanning, the feed being displaced in opposition to the rotation of the reflector to give a momentarily stationary beam; after a few degrees, the feed is rapidly moved back to produce a stepping motion of the beam. Application of this principle gives rise to the modified curves of Fig. 2-6. The major changes occur at the short wavelengths: at 70 cm, the improvement is negligible; at 10 cm, improvements ranging from 5 db for a 17-foot antenna to 12 db for a 30-foot antenna are in principle obtainable. There is now a slight preference for the shorter wavelengths for any given antenna size. It is necessary to point out that step scanning makes it impossible to apply the beam-splitting techniques now used to provide the accuracy necessary for guiding interceptions. Monopulse systems could be devised to overcome this difficulty, further complicating both the antenna design and MTI circuitry.

Clutter-spectrum widening due to aircraft motion can also be overcome in principle. It is possible by the use of multiple-feed points to displace the effective center of reception between pulses so that, when two successive pulses are compared, the phase changes ordinarily introduced by the motion of the aircraft during the pulse interval are eliminated. The displacement required along the antenna is $2\tau V \sin\theta$, where τ is the pulse interval (1/300 sec), V the velocity of the aircraft (300 ft/sec) and θ the angle of the beam off the ground track. While the maximum displacement required is

one foot, the displacement must be varied with the scan angle and the aircraft ground velocity. The use of this system will degrade the range performance of the radar, since the average power received is cut in half.

The application of both step scanning and displaced-phase-center antennas could presumably reduce the clutter-spectrum width to that caused by motion of the scatterers themselves. There are, however, practical limits to the perfection of cancellation that can be achieved, due to nonlinearity in circuit elements, multiple reflections in the delay line, etc. For this reason, an upper limit of 35 db in the cancellation ratio has been assumed here, and no value larger than this has been used in calculating the contours shown.

Figure 2-7 shows the contours of clutter-to-target ratio resulting from application of all three principles: double-delay MTI, step scanning, and displaced-phase-center antennas. Here the 35-db practical limit determines the values on the curves, which become straight lines on the log scales used.

The relative desirability of using any or all of these methods under a particular set of circumstances may be seen by reference to Table 2-V which gives the clutter-to-target ratios for a 30-foot antenna.

TABLE 2-V

CLUTTER-TO-TARGET RATIOS FOR VARIOUS MTI METHODS

Wavelength (cm)	With Double-Delay MTI (db)	Add Step-Scan (db)	Add Displaced Phase-Center Antenna (db)
25	30	24	22
45	28	28	24
70	29	29	27

It is evident that these relatively complex additions to the radar do very little at 70 cm, but at 25 cm they do give some improvement.

RECOMMENDATIONS

A requirement for AEW&C radars could be written from data that can be found in the Introduction and Sec. II of this chapter and in Appendix 2-A. At this stage, the requirement would be limited in its demands by the estimated cross sections of enemy aircraft, by estimated ceilings of the bombers, and by the estimated capabilities of our own AEW aircraft. The requirement would be for

a search and control radar which, when carried by an airplane at an altitude of 20,000 feet, would detect all 2-m^2 targets with an 80 per cent cumulative probability of detection at the horizon range of 180 miles, and this performance should be the same at all altitudes from the surface up to 60,000 feet. Further, the radar would be required to track these targets from its maximum detection range inward to within a few miles of its own location. The horizontal beamwidth of the radar would be required to be less than 5°; the shape of the beam in the vertical would be set by the altitude coverage. Height-finding data would be required on all targets from the radar out to a range of 180 miles; the accuracy required from the height finder would be such as to permit targets at altitudes greater than 16,000 feet to be located to within ±8000 feet and to permit all lower-flying targets to be specified as below 16,000 feet.

Clutter returns from the land and the sea constitute a major limitation on the performance of all airborne radars; it is because of clutter that the "requirement" is not met by the existing AEW aircraft, and it may be that, for the same reason, the requirement cannot be fulfilled completely in the future. In Sec. II of this chapter and in Appendix 2-B, an attempt has been made to explain the nature and extent of the limitation imposed by clutter on a variety of radars of widely different design; the data presented in Sec. II now serve as a guide in choosing the parameters of new radars that, it is predicted, will meet the military need more closely than do existing AEW sets.

Clutter calculations and, in the end, predictions concerning airborne radar sets, rest on experimental measurements of clutter. This statement leads to a warning and a strong recommendation. Sea-clutter characteristics have been measured by a number of experimenters and for a moderate range of wavelengths; although fundamental data on sea returns are still far too scant, it does not seem likely that new measurements will lead to serious revisions in these calculations. For this reason, it is felt that trust can be placed in the predictions of the performance of radars over the sea. On the other hand, except for measurements at a wavelength of 3 cm, data on the clutter returns from land hardly exist. From a general knowlege of the physical properties of clutter, it is possible to predict that, over land surfaces, one radar will perform better than another; but it is not possible to say that, under given circumstances, a radar will perform well enough. Because of this lack of fundamental data, millions of dollars could be wasted on the development of radars which when used over land would fail to give satisfactory performance. It cannot be recommended too strongly that a full-scale program, aimed at the collection of data on land clutter at wavelengths scattered over the whole radar spectrum, be started at once. Immediate investigation is needed of the properties of clutter from all types of terrain and particularly the

terrain found in the Canadian North, from the polar ice fields and from the Greenland ice cap.

It is recommended that a major effort be made to procure and to place in operational use the 4 radars that are discussed in the next few paragraphs. In order to realize the capabilities of these radars, it is recommended that an equal effort be made to make available, as soon as possible, an aircraft designed or modified to carry a rotating antenna 30 feet long by 8 feet high. When equipped with this antenna and when loaded with the radar gear, the aircraft should be capable of cruising at 170 knots at an altitude of 20,000 feet. (The performance of the radars would improve if a still lower cruising speed should be possible.) In making these recommendations, an abrupt change in radars and aircraft is not proposed. Until modification kits, new radars and new aircraft are available, the existing equipment will perform the AEW function; when new equipment appears, a program of modification is possible that discards very little of the present equipment and that will result in a completely modified AEW system for the 1958-1960 period. The recommendations that follow have been placed in an order that corresponds to the probable chronological appearance of the equipment. No time period has been associated with them, for it is believed that, after 1957, the time required to make the radars operational depends only on the effort that is put into procuring them.

Over the sea, the "requirement" on a search and control radar can be met in detail. As a first step, it is recommended that modification kits be procured that will convert the APS-20B radar into a 2-Mw, 70-cm set. This modification kit, in fact, has been partially developed and a radar of similar characteristics has been flight-tested. Since this set operates with a 17 × 4 foot antenna in the existing radome of the WV-2, its beamwidth of 9 to 10° is much wider than the 5° beamwidth that has been specified for the control function. It is recommended that the kit convert the APS-20B into a set that will have a pulse length of 6 μsec and a recurrence frequency of 300 pps, and that will be equipped with double-delay, clutter-locked MTI. When flown at 20,000 feet over rough seas and used to detect a B-47 target, it is predicted that this radar will have a range for a 50 per cent blip-scan ratio of 145 miles. With the MTI system operating, it is predicted that clutter will not interfere with detection at any range even over the roughest sea. Over land, because data are not available concerning the reflectivity of the terrain at a wavelength of 70 cm, the performance of the radar cannot be predicted, but in that service its performance (except in relation to beamwidth) is not expected to be inferior to the APS-20B. Over terrain that causes excessive clutter, it

may be necessary to fly the radar at a very low altitude and to use it to detect only those targets that are above and beyond its horizon. This radar is described in Ref. 1.

A modification kit to convert the APS-45 radar into a 2-Mw, C-band, nodding-beam height finder is recommended as the next change to be made in the equipment of the existing WV-2 aircraft. The antenna for this height finder would be installed in a modified radome above the fuselage; it is recommended that the vertical dimension of this antenna be at least 8 feet and that the area of the aperture be at least 40 square feet. This radar would operate with a one-microsecond pulse at a recurrence frequency of 300 pps; a second and higher repetition rate would be incorporated for aural raid-size evaluation. The free-space range on a B-47 target is predicted to be 180 miles. At 180 miles over rough sea, the height finder would measure height at its full data rate on all targets above an altitude of 25,000 feet and at a reduced data rate on targets down to about 18,000 feet. For comparison with the APS-45 height finder, at 75 miles over rough sea the C-band radar would be capable of finding height on all targets above an altitude of 18,000 feet and at a reduced data rate on targets down to 12,000 feet. It is believed that the time of delivery and the cost of production of this kit would not be excessive if it were designed to make use of the modulator of the APS-20B radar and if full use were made of components from the APS-45. Assurance has been received from the designers of the WV-2 that the new radome would not cause much deterioration in the performance of the aircraft. Details concerning this radar can be found in Appendix 2-C.

The "requirement" will be approached rather closely only when antennas larger than those in the WV-2 aircraft are available, and to this end it has been urged that a large aircraft be modified to carry a 30 × 8 foot rotating antenna. It is recommended that two new radars be installed in this aircraft: a 4-Mw UHF search set, and an S-band, stacked-beam search and height-finding radar; it is planned that the two radars make common use of a single radome. This combination, a large antenna and two high-powered sets, will provide capability for detection and control to the horizon at all target altitudes over both rough sea and land, height-finding, good resolution, and a considerable resistance to countermeasures.

The new UHF search set is planned to operate with a peak power of 4 Mw, a recurrence frequency of 300 pps, and a pulselength of 2 μsec, and to be equipped with double-delay, clutter-locked MTI. The reduced pulselength makes possible higher target-to-clutter ratios, and the large antenna not only reduces the beamwidth to the required 5° but also improves MTI operation. Over the sea, the maximum range of the radar on a B-47

target is predicted to be 250 miles, and sea clutter is not expected to interfere with detection at any range. Over land, the maximum range of the radar would be 190 miles.

The second new set, an S-band, 5-Mw, stacked-beam radar of somewhat special design is planned to operate both as a search set and a height finder. It would operate with a one-microsecond pulse at a recurrence frequency of 300 pps; its free-space detection range is estimated to be 200 miles. As an adjunct to the UHF set, this S-band radar would give high resolution at the higher altitudes in all sea states, and in some sea states could be used for high resolution down to the sea surface. As a height finder, over rough sea, target altitudes may be determined at 80 miles on all targets at altitudes greater than 12,000 feet, at 160 miles on all targets above 20,000 feet. As in the case of the UHF set, its performance over land cannot be predicted because of lack of information, but it is known that the large antenna will lead to successful performance over a larger portion of the North American continent than is now possible. A detailed discussion of the stacked-beam, S-band radar can be found in Appendix 2-C.

New jamming methods constitute a serious threat to the operation of the air defense system. It is recommended that these new radars be designed to be tunable over a wide range.

New and as yet untested designs which are intended to minimize clutter have been avoided in the 4 radars that have been recommended; nevertheless, it is believed that some of these special methods may become of great importance in the design of airborne radars. Two general techniques have been suggested as ways in which MTI performance could be improved by reducing the width of the clutter spectrum. These have been called, respectively, displaced-phase-center operation and step scanning, and both methods have been described in Sec. II of this report. Target-to-clutter ratios before MTI filtering can be improved by using very short pulses. Means of obtaining the effect of short pulselengths without the need of high peak power have been suggested; of these methods, frequency modulation during the pulse is one, and other methods of tagging portions of the pulse are known. It is recommended that research and development in these fields be encouraged.

REFERENCE

J. Freedman, et al., "Comparative Performance of 10-cm and 70-cm Radar over the Sea," Technical Report No. 56, Lincoln Laboratory, M.I.T. (25 August 1954).

CHAPTER 2 RECOMMENDATIONS

1. *We recommend a major effort to make available, as soon as possible, an aircraft designed or modified to carry a rotating antenna 30 feet long by 8 feet high; this aircraft should be capable of carrying the radars recommended (below) at an altitude of 20,000 feet; its cruising speed should not be in excess of 170 knots.*

2. *We recommend an equal effort to procure and to put into operational use the following four radars:*

for the present WV-2 aircraft:

(a) A 2-megawatt UHF (70-cm) search set to operate with a new 17 × 4 foot antenna in the present WV-2 aircraft. It is proposed that this radar have a pulselength of 6 microseconds, a recurrence frequency of 600 pps, and double-delay, clutter-locked MTI.

(b) A 2-megawatt C-band (5-cm) nodding-beam height finder to operate with an 8-foot antenna in a modified radome above the fuselage of the present WV-2 aircraft.

for the new or modified aircraft:

(c) A 4-megawatt UHF (70-cm) radar to operate with the 30 × 8 foot antenna in the new aircraft. It is proposed that this radar have a pulselength of 2 microseconds, a recurrence frequency of 300 pps, and double-delay, clutter-locked MTI.

(d) A 5-megawatt S-band (10-cm) stacked-beam radar of special design to operate in the new aircraft both as a height finder and as an adjunct to the search set. This set is to use either the same 30 × 8 foot antenna as the search set, or a separate antenna in the same rotadome.

3. *We recommend a modification program to convert, beginning in 1956, the existing APS-20B radars to the UHF search radars shown under 2(a), and to convert the existing APS-45 height finders to the C-band height finders shown in 2(b). During the 1958-1960 period, the modified aircraft with a 30 × 8 foot antenna can become operational with the high-power UHF search radar shown under 2(c) and with the S-band stacked-beam radar shown under 2(d).*

4. *To counter the jamming threat, we recommend that these new radars be designed to be tunable over a wide range.*

5. *We recommend research and development on all methods of minimizing clutter,*

with particular attention to the following techniques:

(a) The reduction of scanning clutter by step-scanning methods,

(b) The reduction of platform clutter by displaced-phase-center operation,

(c) Frequency modulation or other methods of tagging portions of the pulse to obtain the effect of short pulselengths without using high peak powers.

6. *We recommend that an aircraft be instrumented for the measurement of clutter at a variety of wavelengths ranging from 3 to 70 cm, and that a large-scale study of land clutter be initiated, especially over northern Canada (60°N) and over the polar ice fields and the Greenland ice cap.*

APPENDICES TO CHAPTER 2

APPENDIX 2-A
RESOLUTION REQUIREMENTS IN AEW RADAR

INTRODUCTION

The functions of an AEW&C aircraft include detection, raid-size assessment, and control of interceptors. The degree to which these functions can be carried out depends critically not only on the choice of radars for the control craft, but also on the capabilities of the interceptor's AI radar. The advantages of UHF radar with regard to freedom from clutter and long detection ranges may be offset or completely negated if the wide beamwidths degrade seriously the ability to carry out the other necessary functions.

The problem has three main aspects:

Assessment of size of raid,
Assignment of interceptors to targets,
Guidance of interceptors.

ASSESSMENT OF RAID SIZE

In order to resolve two aircraft on the PPI, it is necessary that their ranges differ by at least a pulsewidth, or that their azimuths differ by an angle larger than the antenna beamwidth. Because the width of a blip on the PPI is a function of the strength of the signal, it is in general not possible to determine the presence of multiple targets by a widening of the blip. Thus the resolving power of a radar is much worse in general than the angular accuracy.

Figure 2A-1 illustrates the least resolvable elements of two radar combinations at several ranges. While the angular scale is grossly exaggerated, the linear dimensions of the blocks are properly proportioned.

The upper figure shows an APS-20B with 1.5° horizontal resolution, together with an APS-45 height finder with a vertical beamwidth of 1°. At 100 miles (a generous range for these two), the least resolvable element is 1.7 × 2.6 × 0.2 miles. The UHF radar (30-foot antenna) shows at 100 miles a resolution block 1.7 × 8.6 × 0.2 miles. At longer ranges, the width goes up proportionally, the depth increases to 0.5 mile, while height resolution is completely lost because of the limited range of the APS-45 height finder.

In order that a group of planes pass as a single target, it is necessary that they remain spaced in such a way as to fall completely within one of these blocks. It is somewhat

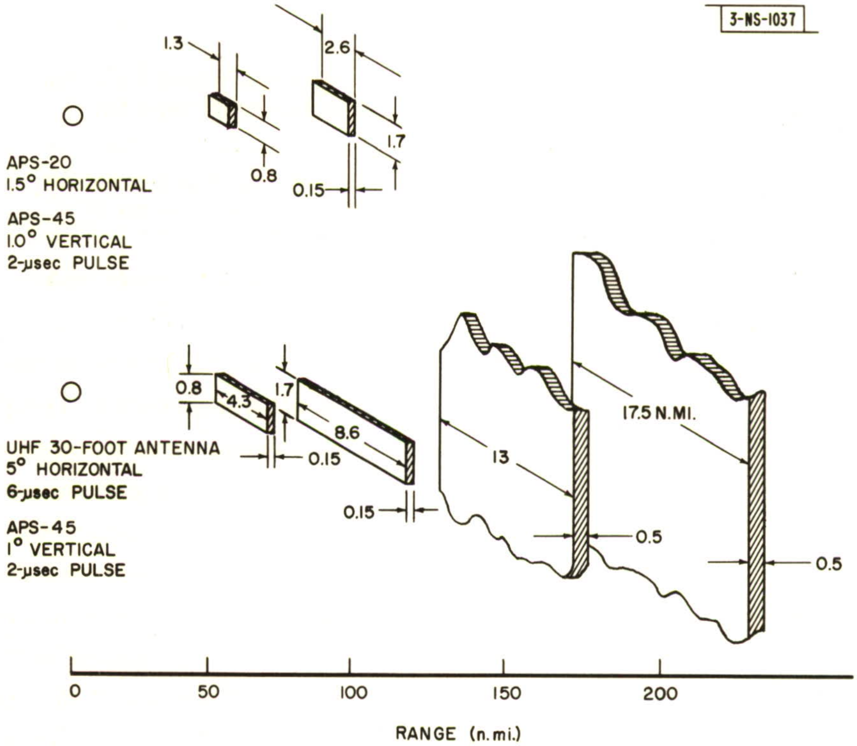


Fig.2A-1. Resolving power, AEW radars (all dimensions in nautical miles).

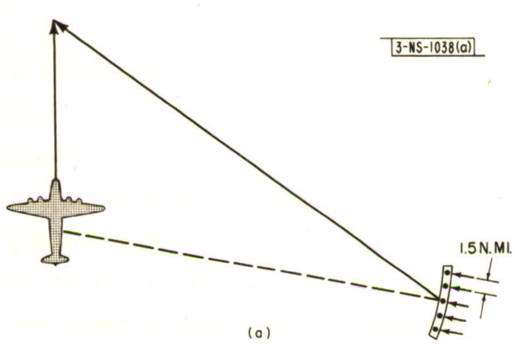


Fig.2A-2(a). Approach to AEW aircraft constant formation angle.

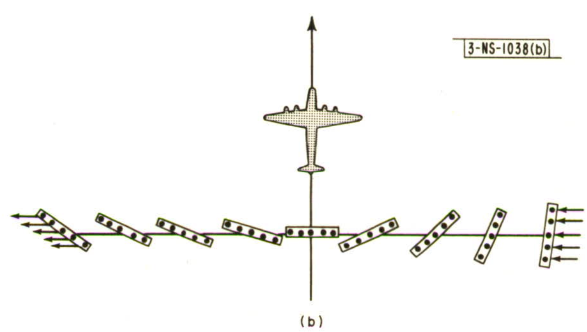


Fig.2A-2(b). Straight-line course through AEW line.

difficult to predict the enemy's tactics in making a penetration, but the following points seem assured:

> In clear weather in daylight, groups of three planes can be flown in formation at spacings of a few hundred feet for several hours at a time.
>
> Loose groups without special station-keeping equipment or visual contact will have difficulty in keeping spacings of less than a few miles.
>
> To avoid high kills from nuclear weapons, a minimum spacing of 1.5 miles will in all probability be employed.

Looking at the shape and size of the resolution blocks, two facts are at once apparent. First, neither of the radar combinations shown is at all competent to resolve a group of three planes flown wingtip-to-wingtip. Second, the range resolution of either of the two radars will in all probability suffice to distinguish loose groups or wide-spaced formation groups. While it is true that, by using ECM listening gear, the planes can be flown in such a way as to keep identical ranges, the tactic is not an easy one. Figure 2A-2 shows two possibilities. In the first, a collision course toward the AEW craft is flown by the squadron leader, and his partners are instructed to fly at the proper angle, which remains constant. The obvious disadvantage of this tactic is that it leads inevitably to the AEW aircraft and recognition as multiples at short ranges. Alternatively, a straight course can be flown, and the angle of the group varied with time as shown in Fig. 2A-2(b). The group takes the chance that it can be seen by only one radar, as it cannot in general satisfy the necessary conditions to be unresolved by both.

Altogether, range resolution, which is available even at long ranges, seems to be a rather powerful tool, and it is to be recommended that shorter pulses (with, of course, higher peak powers) be employed as the state of the art advances. If signal strength is adequate, short pulses without increased power can be employed to help in an assessment. Any increased angular resolution is helpful; it increases the difficulty of stacking planes and increases the range at which positive determination can be made if tactics such as the above are resorted to. If the azimuthal resolution is reduced to the point where it can resolve planes with a $1\frac{1}{2}$-mile spacing at the desired range, it would appear to have a considerable virtue; otherwise, it seems appropriate to depend on improving the already quite-good range resolution and to deny one dimension to the enemy.

The height-finding radar which is a necessary part of the equipment can serve also to obtain further information of the following types:

Beating of pulses as observed on an A-scope,
Listening to the audio spectrum of the boxcar video,
Spectrum analysis of the received video.

Some experience in World War II indicates that, on an A-scope presentation, an experienced operator can sometimes guess that a rapidly fluctuating pip represents a multiple target. In Operation Checkpoint, however, there was little correlation between multiple-target reports and true multiple targets. There seems to be very little quantitative evidence as to the effectiveness of this technique.

Several groups have experimented with audible presentation of the range-gated video envelope. The information derived can be divided into three categories:

Propeller modulation,
Non-coherent Doppler obtained against a clutter background,
Coherent Doppler obtained by beating against a coherent oscillator.

With high-repetition-rate radars and good tracking, excellent reproduction of propeller sounds can be obtained, so that single and multi-engined planes give characteristic sounds which permit them to be readily distinguished. As the repetition rate is reduced below 2 kcps, there is a constant degradation of the information, and at 800 pps the method becomes quite poor. There has been little or no testing against multiple targets, so that it is not possible from the results at hand to estimate the possibilities of raid-size evaluation on propeller-driven planes. The 450-cps repetition rate of the APS-45 height finder does not lend itself well to this task.

When jet planes are flown against a coherent radar, a very clean Doppler note is produced. Because targets displaced in position will have somewhat different radial velocities with respect to the radar craft, their Doppler notes will in general have different frequencies.

In a typical case, one could expect at X-band Doppler frequencies of the order of 10 kcps, an uncomfortably high value in view of the 450-pps repetition rate of the height finder. However, some information can certainly be derived from the Doppler frequency difference, which is of the order of 10 to 200 cps. This is what is normally displayed on the A-scope; a more complete frequency analysis of the returned video, even if it is just the use of the ear instead of the eye, might well pay dividends. Provision should be made for doubling or tripling the repetition rate of the height finder when used for this purpose.

In conclusion:

> Range resolution provides good multiple-target assessment even in the absence of angular resolution.
>
> For the expected target groupings and desired ranges, a 2° radar is not greatly superior to a 5° or even a 9° radar, provided the pulse length is sufficiently short to enforce the conditions illustrated in Fig. 2A-2.
>
> Within the range of the height finder, audio analysis of the returned video might permit one to distinguish propeller-driven from jet aircraft, and single from multiple jets.

ASSIGNMENT OF INTERCEPTOR TO TARGET

Even though, by one of the techniques described, a signal may have been identified as consisting of several targets, the possibility of assigning a target to each interceptor, so as to avoid over-kills, depends on actually being able to track each target uniquely. Here azimuth resolution is of great help to prevent confusion and to assess results of the attack. Range resolution is also of benefit, but to a lesser degree. If it is assumed that the attack will come in groups of large numbers of aircraft, fairly closely spaced, then none of the radars described is really adequate for a one-to-one assignment job, except at short ranges.

GUIDANCE OF INTERCEPTIONS

The successful conclusion of an interception depends on many factors, not the least of which is the ability of the control radar to guide the intercept to a point where the target is within lock-on range and the bearing of the interceptor with respect to the target and the heading of the interceptor are such as to permit a successful maneuver to the aiming and firing point.

The interception-guidance problem has been studied quantitatively for certain cases by Bell Telephone Laboratories.[1] They find it convenient to specify the interception in terms of the two variables of interceptor bearing from the bomber and interceptor heading error from a collision course. For each lock-on range, a diagram (Fig. 2A-3) can be constructed in these coordinates, showing the limits set by:

> AI radar look angle,
> Vulnerability of interceptor to tail armament of bomber,
> Maneuverability of interceptor.

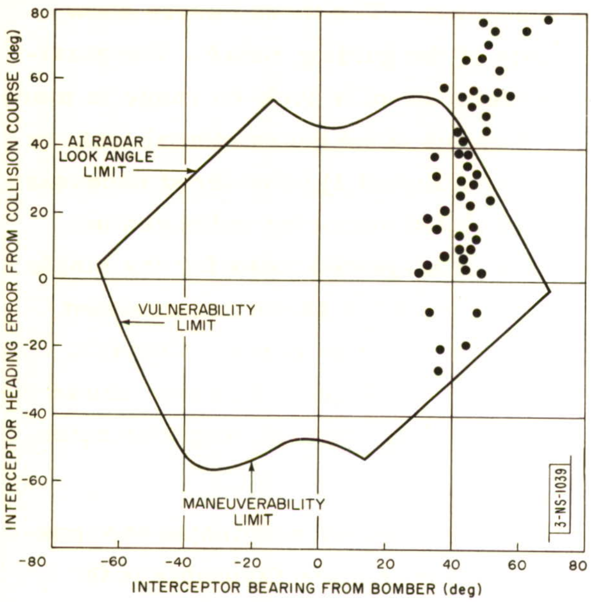


Fig.2A-3. Vectoring phase performance in attack-vectoring plane, 6 nautical mile lock-on range (Bell Telephone Laboratories, Case 26656-1, W.H. McWilliams).

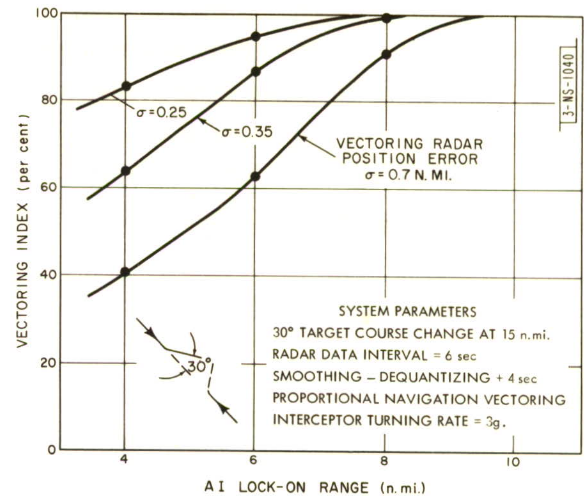


Fig.2A-4. Vectoring index vs AI lock-on range for various vectoring radar position errors. Each curve based on 25 interceptions made with random target data errors (Bell Telephone Laboratories, Case 26656-1, W.H. McWilliams).

These limitations in general define an area in the bearing angle-heading error plane, within which a successful intercept can be made.

The uncertainty in the vectoring is made up primarily of 3 factors:

> The quantized nature of the information due to scanning,
>
> Lack of accuracy ("noise") in azimuth and range,
>
> Errors in response of the interceptor to instructions from the control.

These uncertainties result in a different trajectory for each interception carried out, even though the initial conditions are identical. At any lock-on range, the trajectory appears as a point on the aforesaid plane, and a series of such runs made on a simulator will result in a scatter diagram of points, which may fall partly within and partly outside the delimited area. The fraction of points that fall within the limits is called the vectoring index; it represents the probability that the guidance employed for that particular geometry will result in a successful intercept.

The numerical value of the vectoring index depends very strongly on lock-on range, and less strongly on the data rate and the errors in position determination. Figure 2A-4 shows a typical set of curves obtained for a rocket attack at 600 knots against a

600-knot bomber which makes a 30° 1g evasive maneuver. The three curves show the variation due to changing the position uncertainty of the guiding radar. The maximum error used in this study was 0.7 mile. Note that a 10-mile lock-on range is more than adequate under these conditions. Figure 2A-5 shows some experimental lock-on probability curves, together with a hypothetical curve (labeled 3) considered necessary for this type of attack. With these curves, an accumulated vectoring index can be derived which is somewhat more meaningful than the unintegrated index for the single lock-on range postulated for the previous curves. Figure 2A-6 shows accumulated vectoring indices as a function of data interval and radar position error. Curve 3, which represents a hypothetical 80 per cent probability of lock-on at 9 miles, shows very good performance and, if extrapolations are at all to be trusted, might be satisfactory even for position uncertainties of 2 miles.

The above examples have been taken for rocket armament, which eliminates the possibility of a tail-cone attack. With missiles, the situation is more favorable with respect to tail attacks. More recent studies, as yet incomplete, have been carried out at BTL for the case of missile armament and wide radar beams.

The parameters used in the simulation are shown in Table 2A-I.

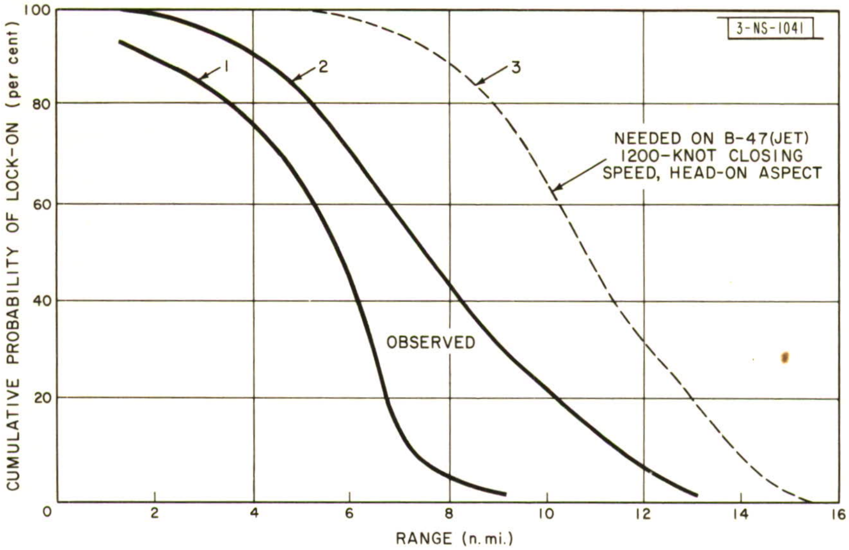
TABLE 2A-I

PARAMETERS OF BTL INTERCEPT-GUIDANCE SIMULATION

Radar beamwidth	18°
Azimuthal error	±1.8°
Range from control radar	80 n. mi.
Position error	±2.5 n. mi.
Target speed	600 knots
Interceptor speed	750 knots
Approach	30° from the nose, with the target performing a 30° evasive turn at 1g

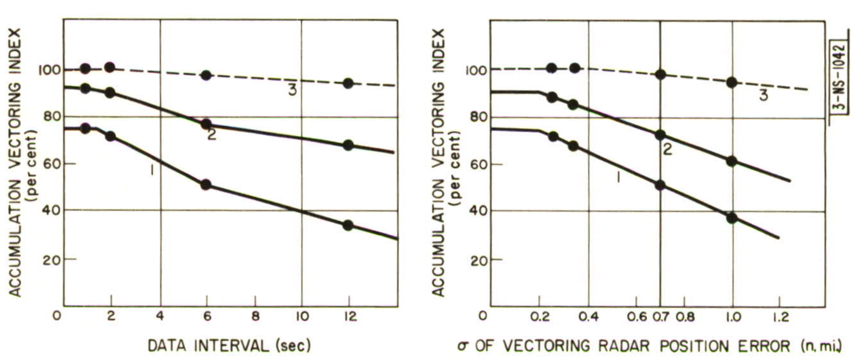
Preliminary results indicate that an 8-mile lock-on range is quite inadequate, that at 10 miles successful interceptions are possible if the evasive turn is not inward, and that a 15-mile lock-on range is very satisfactory.

Though studies at BTL are not complete, it is felt by those concerned that the results are fairly certain of eventual corroboration in detail. At a 15-mile lock-on range,

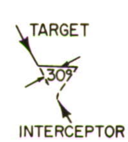


	CURVE	AIRCRAFT	CLOSING SPEED	ASPECT	RADAR
1.	OBSERVED	F9F (JET)	610 Knots	HEAD-ON	E-10
2.	OBSERVED	F8F (PROP)	50 Knots	TAIL-ON	APQ-41
3.	NEEDED	B-47 (JET)	1200 Knots	HEAD-ON	

Fig.2A-5. Observed and needed cumulative AI lock-on probability vs range (Bell Telephone Laboratories, Case 26656-1, W.H. McWilliams).



	CURVE	AIRCRAFT	CLOSING SPEED	ASPECT
1.	OBSERVED	F9F (JET)	610 Knots	HEAD-ON
2.	OBSERVED	F8F (PROP)	50 Knots	TAIL-ON
3.	NEEDED	B-47 (JET)	1200 Knots	HEAD-ON



30° BOMBER COURSE CHANGE AT 15 mi.
CENTRAL CASE: DATA INTERVAL = 6 sec
σ OF POSITION ERROR = 0.7 n.mi.

Fig.2A-6. Accumulated vectoring index vs vectoring radar data interval and position error (Bell Telephone Laboratories, Case 26656-1, W.H. McWilliams).

the only limitation remaining is that of the radar look angle; the maneuverability limit has been removed, as well as the vulnerability limit.

In these studies, BTL made no allowance for missile-preparation time after lock-on. These times may in some cases be fairly important. Cornell Aeronautical Laboratory has studied the attack problem for several missiles and, while there are many complexities involved, the general statement can be made that the worst case can be satisfactorily handled if a detection range of 12 miles can be provided.

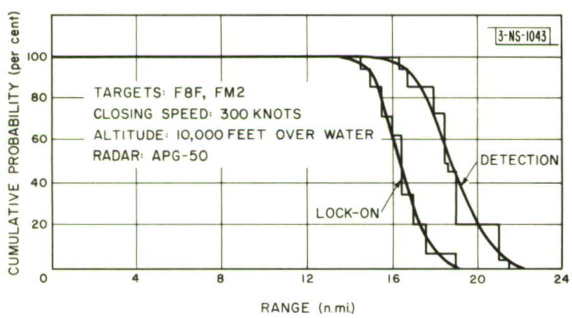


Fig. 2A-7. Detection and lock-on ranges of AI radar.

Some recent test results on the lock-on range of the APG-50 fire-control radar are shown in Fig. 2A-7. These would indicate that lock-on ranges of 15 miles or more may be well within reach. On the basis of the above figures, a 9° beamwidth does not appear too wide for successful intercept guidance at a range of 160 miles.

So far, only the case of guiding a single interceptor directly from the control aircraft has been discussed. For large numbers of targets, manual control will not suffice, and it may be desirable to integrate the AEW radar into the shore net.

The SAGE System operates with a least count of 0.1° in azimuth. The accuracy of data required is 0.2° in azimuth and 1/4 mile in range. Though the system is intended to operate with the FPS-3 radar, which has a beamwidth of 1.3°, recent tests using a TPS-1D with a 5° beamwidth have given gratifying results. The beam-splitting technique, which essentially consists of finding the center of gravity of a group of echo pulses that have been selected as being above a given threshold, is apparently quite competent to give a 0.2° rms error with a 5° beam. About 64 hits per beamwidth are used. Successful beam splitting depends on having a signal several db above noise.

While no tests have as yet been made of the SAGE System with radar beams wider than 5°, it is the opinion of J. V. Harrington of Lincoln Laboratory that performance will probably be considerably degraded. However, it is too early to say that 9° beams cannot be used with the SAGE System.

When the aircraft is used to relay intercept information for ground control, accurate information as to its position and heading is required. It has been proposed to use a double-beacon system, where the ground radar observes the azimuth and range of the

control aircraft, and the control aircraft observes the beacon on the ground to provide heading information. While the larger beamwidths give correspondingly larger errors in apparent heading, 5° beams will not deteriorate the system very much, especially since the error in most cases is common to both target and interceptor. This system requires that the AEW craft stay within sight of the ground radar.

WPS?

Taking into consideration the various situations that may be encountered, it is concluded that a radar with a 5° beamwidth should be adequate for manual control of high-speed interceptions at distances of 150 miles, provided the AI lock-on range is 10 miles or more. (Note that missile-preparation time may increase this requirement.) It could also be made compatible with the SAGE System if the signals are reasonably clean. A 9° radar will provide successful high-speed interceptions at 150 miles if the AI lock-on range exceeds 15 miles. There is some doubt as to whether a 9° radar would operate satisfactorily with the SAGE System.

AEW HEIGHT-FINDER REQUIREMENTS

The requirements on a height-finding radar are closely related to the capabilities of the AI and AEW radars.

If control of the interception is demanded of the AEW radar, then it is necessary that the height finder have a maximum range capability equal to that of the AEW radar, i.e., 180 miles.

The permissible inaccuracy of height finding is determined by the AI detection and lock-on range. Since the AI radar has a vertical search pattern covering about 16°, it may fail to detect the target if the latter lies more than 5000 feet off the axis of search when the interceptor is 6 miles away, or 8000 feet at 10 miles. Thus one must certainly set an upper limit of ±8000 feet error in the height finder; at 180 miles this is ±0.2°. A larger vertical search angle in the AI radar would permit relaxation of the height-finder requirements. In certain cases, large horizontal search angles may not be required, and the frame time could be used for searching over greater heights.

The interceptor must also be able to make a proper approach after lock-on. While there are very little data on the degradation of intercept performance when height errors are introduced, the vertical angles involved are small compared to the azimuthal angles at the early stages, so that, again, if the AI lock-on range exceeds 10 miles, a vertical error of one mile should not be serious.

OH GREAT!

It is never required that the interceptor search below the surface of the terrain; thus for low targets it will suffice for AI search purposes if the height finder reports the target as being below 16,000 feet.

The figures quoted here probably represent the maximum tolerable error; in view of the difficulties of carrying out interceptions in general, much smaller errors would be welcome, though it is doubtful whether they can be attained readily from AEW craft at long ranges. It is important to note that these figures are predicated on an AI performance of a relatively high quality for present-day interceptors. They emphasize again the importance of achieving longer ranges in AI radar.

Height data are required by the SAGE System, in order to control intercepts. Integration with SAGE will thus require transmission of height information along with the search-radar message. This requires coordination within the AEW aircraft, to consolidate the data before transmission. SAGE is designed for 1000-foot height intervals, but will accept coarser data.

J. W. Coltman

REFERENCE

1. W.H. McWilliams, Jr., "The Navy Intercept Project at BTL," Case 26656-1, Bell Telephone Laboratories.

APPENDIX 2-B

CALCULATIONS OF AEW RADAR PERFORMANCE OVER LAND AND SEA

INTRODUCTION

The recommendations made in Chapter 2 are based largely on lengthy calculations of AEW radar performance over land and sea. The purpose of this appendix is to present the method of calculation and to indicate the potential sources of error. The properties of sea return and land return are so different, and their effect on AEW radar performance is so marked, that it will be simpler to discuss AEW radars over sea and land as separate cases.

AEW RADARS OVER SEA

Choice of Parameters

The principal independent variables in these calculations were antenna size and radar wavelength. It would have been possible, in principle, to determine the functional relationship of all important radar parameters to these variables, and then to optimize the maximum range, clutter-free range, resolution, etc. There was insufficient time and information available to the group, however, to allow this program to be carried out rigorously. The procedure adopted was to select a small number of wavelength bands and antenna sizes which were believed to be characteristic from the standpoint of radar and aircraft performance, and then to "design," for each of these cases, radars that represented a qualitative optimization (based on previous trial calculations) with respect to coverage and clutter-free range. The values of peak power, average power and noise figure were chosen on the basis of a moderate extrapolation of the present art at each wavelength. This process resulted in 18 "designs," whose principal characteristics are summarized in Table 2B-I.

A radar height of 20,000 feet was assumed in all cases. This value was chosen in a desire to minimize AEW aircraft force requirements by having the largest possible horizon range consistent with other "cost" considerations. A height of 20,000 feet appears to be an optimum because, above this height, horizon range increases very slowly and because the aircraft-design problem becomes very severe for the antenna sizes of interest.

For the clutter calculations, it was assumed that the target was flying just above the sea surface, the most pessimistic assumption, since no height gain in target-to-clutter ratio can be realized under these conditions. A target cross section of two square

TABLE 2B-1

EIGHTEEN AEW "DESIGNS" PROPOSED BY PROJECT LAMP LIGHT

Wavelength	10 cm (3000 Mcps)				25 cm (1200 Mcps)					35 cm (830 Mcps)			45 cm (650 Mcps)			70 cm (435 Mcps)		
Parameters / Case	I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII	XIII	XIV	XV	XVI	XVII	XVIII
Antenna type	csc^2		csc^2		csc^2		csc^2											
Antenna dimensions (ft)	17 × 4	17 × 4	30 × 5	30 × 5	17 × 4	17 × 4	30 × 5	30 × 5	60 × 7	17 × 4	30 × 5	60 × 7	17 × 4	30 × 5	60 × 7	17 × 4	30 × 5	60 × 7
Antenna area (ft^2)	68	68	150	150	68	68	150	150	420	68	150	420	68	150	420	68	150	420
Antenna gain (db)	32	35	35.5	38.5	24.5	27.5	28.5	31.5	35.5	24.5	28	32.3	22	25.5	30	18.5	22	26.5
Horizontal beamwidth (deg)	1.4	1.4	0.8	0.8	3.5	3.5	2.0	2.0	1.0	5	2.8	1.4	6.4	3.6	1.8	10	5.6	2.8
Vertical beamwidth (deg)	5.4	5.4	4.3	4.3	13.5	13.5	10.8	10.8	7.7	19	15.3	10.8	25	20	14	41	32	22
Prf	300	900	300	300	300	300	300	300	300	300	300	300	300	300	300	300	300	300
Peak power (Mw)	2.5	2.5	2.5	2.5	10	10	10	10	10	10	10	10	10	10	10	10 (5Mw 1957)	10	10
Noise figure (db)	9	9	9	9	8	8	8	8	8	7	7	7	6	6	6	4	4	4
Pulse duration (μsec)	2	0.6	2	2	0.5	0.5	0.5	0.5	0.5	1	1	1	1.5	1.5	1.5	2	2	2
Sea reinforcement (db)	0	0	0	0	1	1	1	1	1	2	2	2	3	3	3	6	6	6

SECRET

Hits/scan	12	36	6.7	6.7	29	29	17	17	8	42	23	12	53	30	15	83	46	23
Range over sea (n. mi.)	102	125	142	195	83	117	124	175	255	140	191	290	149	210	320	186	265	410
σ_w	32	32	32	32	13	13	13	13	13	1.43	1.43	1.43	1.1	1.1	1.1	0.7	0.7	0.7
σ_L	5	5	5	5	2	2	2	2	2	9.1	9.1	9.1	7.1	7.1	7.1	4.6	4.6	4.6
σ_s	12	12	22	22	5	5	9	9	17	3.5	6.2	12.4	2.7	4.8	9.6	1.7	3.1	6.2
σ_v	17	17	10	10	17	17	10	10	5	16.6	9.4	4.7	16.6	9.4	4.7	16.6	9.4	4.7
$\Sigma\sigma_L$	21	21	25	25	18	18	14	14	18	17	12	13	17	11	11	17	10	8
$\Sigma\sigma_w$	63	63	64	64	22	22	19	19	22	19	15	16	18	13	13	17	11	9
Knots	170	170	170	170	170	170	170	170	170	170	170	170	170	170	170	170	170	170
MTI Improvement (land)																		
SD	13.5	23	12	12	15	15	17	17	15	15	18	18	15	19	19	15	20	22
DD	19.5	38	17	17	22	22	26	26	22	23	29	28	23	30	30	23	32	35
MTI Improvement (water)																		
SD	5	13.5	5	5	14	14	14	14	14	14	16	16	15	18	18	15	19	21
DD	8	19.5	8	8	20	20	21	21	20	21	25	24	22	28	28	23	29	34

meters was assumed throughout as characteristic of the B-47 in its least favorable aspects. The radar platform was assumed to be moving at 170 knots ground speed. The radar scan rate was chosen to be 6-rpm. It was assumed that specular reflection from the surface produces a 6-db improvement in maximum range at 70-cm wavelength, with a gradual decrease with wavelength to 0 db at S-band.

Calculation of Maximum Range

The General Electric Radar Range Computer was used throughout the calculations of maximum range, primarily as a means for easy comparative evaluation of the various sets, rather than as a means for precise determination of performance. However, the value chosen for B-47 target cross section is such that the range figures given do not appear to be inconsistent with experience at 10 cm and 70 cm.

At L-band and S-band, the vertical beamwidths available from most of the assumed antennas were inadequate to give the desired high- and low-angle coverage. This can be remedied by modifying the antenna to produce a csc^2 coverage pattern, with a consequent loss in maximum range, or by using multiple receiving beams in a stacked-beam or monopulse arrangement, which results in an improved maximum range under some conditions, at a considerable cost in complexity. Both of these alternatives were considered in the calculations of maximum range. In Fig. 2B-1, the curve marked "noise limit" shows how maximum range varies under the above assumptions

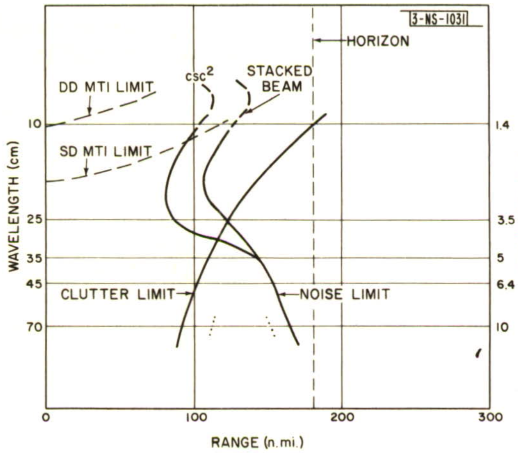


Fig. 2B-1. AEW radar performance, 17 × 4 foot antenna, 20,000 feet, over rough sea. For easy comparison, the radars recommended by Project Lamp Light are shown as segments of the curves (dotted).

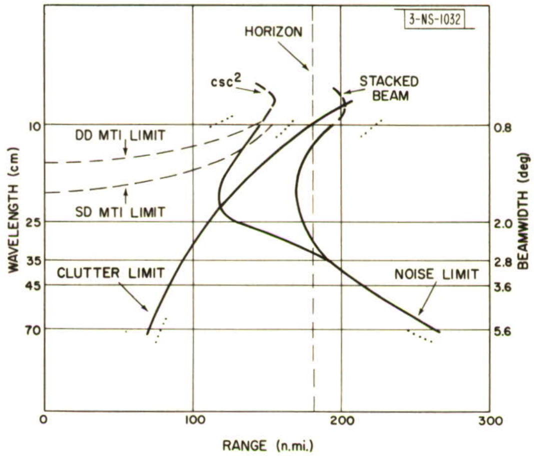


Fig. 2B-2. AEW radar performance, 30 × 5 foot antenna, 20,000 feet, over rough sea. For easy comparison, the radars recommended by Project Lamp Light are shown as segments of the curves (dotted).

for the 17 × 4 foot antenna at 20,000 feet. The branching at short wavelengths illustrates the performance under the "$\csc^2$" and "stacked beam" assumptions. Figure 2B-2 is a similar display of performance for a 30 × 5 foot antenna.

Clutter Spectra and MTI Improvement

The improvement in target-to-clutter ratio obtainable with conventional MTI is a function of the width of the total clutter spectrum (σ_t) and of the pulse repetition frequency (f_r) of the radar. It was assumed in these calculations that this functional dependence is as given in a report by Steinberg and Ashmead;[1] rather than averaging over all velocities, as was done in the reference, the performance for the best velocity was used as shown in Fig. 2B-3. The repetition frequency of the radars is specified in Table 2B-I, and is fixed for most of the designs at 300 per second to match the maximum range requirement. The clutter widths (dispersions) were calculated from the following relations:

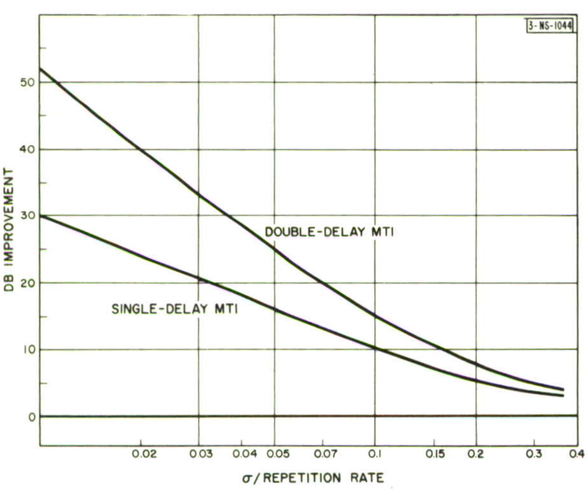


Fig. 2B-3. MTI improvement for best Doppler frequency, not averaged over velocity. (Progress Report No. 11, Philco Tasks under Project Lincoln Subcontract No. 8, Prime Contract No. AF 19(122)-458).

Inherent spectrum of rough sea:

$$\sigma_w \text{(cps)} = 320/\lambda \quad ,$$

Scanning spectrum (calculated for 6-rpm scan rate):

$$\sigma_s = 7.2 \frac{a}{\lambda} \quad ,$$

Platform-motion spectrum (calculated for antenna beam normal to ground track of AEW aircraft):

$$\sigma_v = 1.66 \frac{v}{a} \quad ,$$

Total spectrum width:

$$\sigma_t = (\sigma_w^2 + \sigma_s^2 + \sigma_v^2)^{\frac{1}{2}} \quad ,$$

where

λ = wavelength in cm,

a = horizontal aperture in feet,

v = ground speed in knots.

The improvements obtainable in target-to-clutter ratio using single-delay and double-delay MTI are tabulated in Table 2B-I.

Average Cross Section per Unit Area of Sea Return

A most important parameter of sea return is σ_o, the average cross section per unit area illuminated by a pulse packet. It is a function of sea conditions, wavelength, and angle of incidence. The target-to-clutter ratio (T/C) at any range is the target cross section divided by the product of σ_o and the area of a pulse packet at the same range, i.e.,

$$\frac{T}{C} = \frac{\sigma}{\sigma_o \frac{c}{2} \tau \theta_H R} ,$$

where σ is target cross section, c the velocity of light, τ the pulse duration, θ_H the horizontal beamwidth and R the radar range.

Figure 2B-4 shows the variation of σ_o with α, the incidence angle, for a number of wavelengths and for rough seas. This information was obtained from B. D. Steinberg in a private communication and represents a composite of experimental data from several sources. The angle of incidence over a curved earth is given by

$$\alpha = \frac{H - (R/100)^2}{R} \quad \text{(H and R in nautical miles).}$$

From Figure 2B-4 and the above equation, a graph (Fig. 2B-5) can be constructed showing σ_o as a function of range for a particular height. Then the target-to-clutter ratio can be calculated as a function of range, with and without single-delay and double-delay

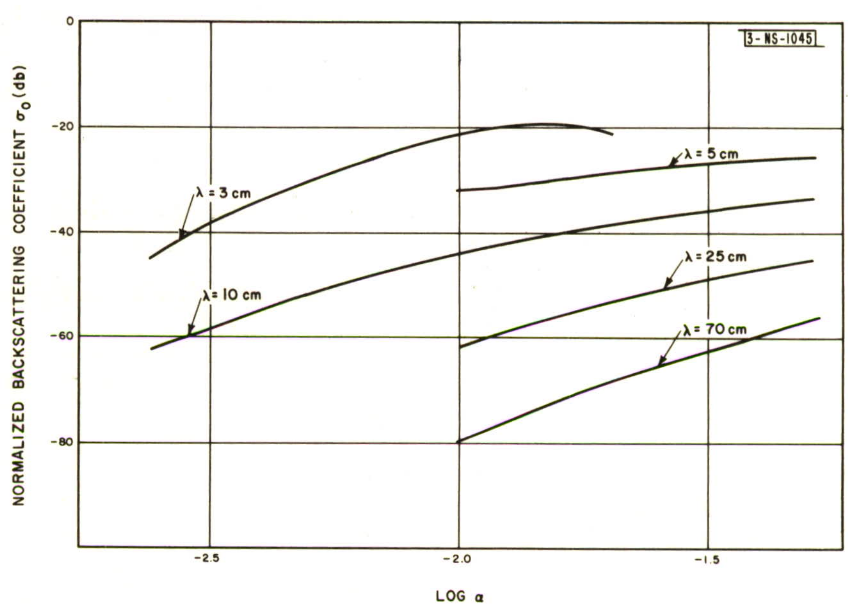


Fig. 2B-4. Backscattering from rough sea vs incidence angle.

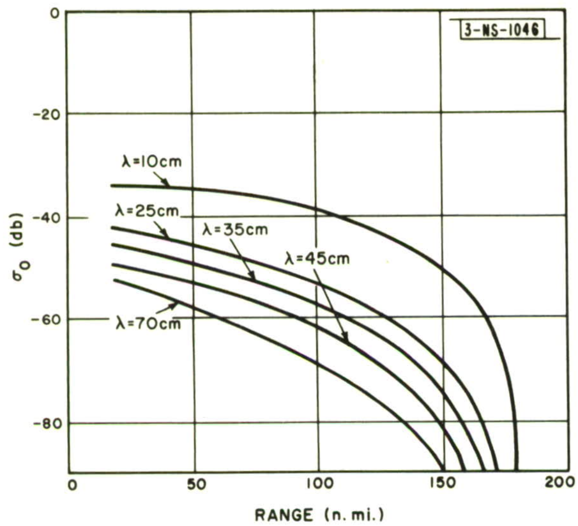


Fig. 2B-5. Backscattering coefficient for rough sea vs range, height 20,000 feet.

MTI. Table 2B-II shows the results of a sample computation of this type. The same procedure was followed for all 18 radars. The curves of Figs. 2B-1 and 2B-2, marked "clutter limit," display the contour of unity target-to-clutter ratio on the wavelength-range plane. Similar curves show this same contour after single-delay and double-delay MTI for the best Doppler frequency (half-way between blind speeds). Figure 2B-6 is a summary of all these results in which contours of constant performance are plotted in coordinates of wavelength and horizontal antenna-aperture plane. Figure 2-4 of the text is a simplified version of Figure 2B-6 in which the range variation has been dropped and only the contour of $R = R_{horizon}$ is plotted. The conclusions drawn from these graphs will be found in Chap. 2.

The recommendations finally made for radar parameters differed slightly from the values used in the "best" designs in these calculations. For easy comparison, the recommended radars appear as segments of the curves in Figs. 2B-1 and 2B-2.

TABLE 2B-II

SAMPLE TARGET-TO-CLUTTER RATIO CALCULATION

Case 16: λ = 70 cm, θ_H = 10°, τ = 2 μsec, 17 x 4 foot antenna

Range (n.mi.)	30	40	60	80	100	120	140	160	180	200
$\frac{\text{Illuminated area}}{\sigma} = \frac{\theta_H R c \tau}{2\sigma}$	1.43×10^6	1.94×10^6	2.91×10^6	3.87×10^6	4.85×10^6	5.85×10^6	6.80×10^6	7.75×10^6	8.75×10^6	9.70×10^6
$\frac{\text{Illuminated area (db)}}{2}$	61.6	62.9	64.6	65.9	66.9	67.7	68.3	68.9	69.4	69.9
σ_o(db)	−53	−53	−59	−64	−69	−74	−83	–	–	–
Target-to-clutter (db) no MTI	−9	−10	−6	−2	+2	+6	+15	+	+	+

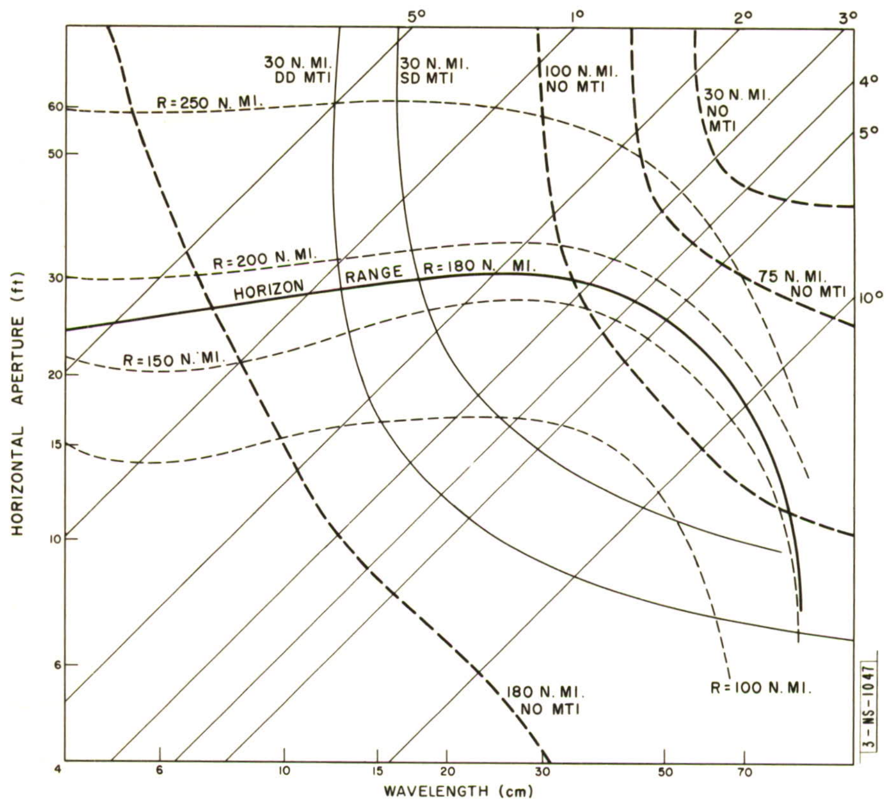


Fig.2B-6. AEW radar performance, 20,000 feet over rough sea, 170 knots, stacked beam branch.

AEW RADARS OVER LAND

Choice of Parameters

The same parameters chosen initially for the case of AEW radar over sea were used in the computations for the over-land case. The justification for this procedure is that the same general criteria apply to each case, the parameters used represent the limits of the radar art, and it is desired, if at all possible, to have the same equipment operable over both land and sea.

It was assumed that specular reflection makes no contribution to maximum range over land at any wavelength considered.

Calculation of Maximum Range

The maximum ranges available from the radars over land are less than ranges over sea at the long wavelengths because of the loss of specular reflection. Table 2B-III indicates the factor by which maximum range at any wavelength over sea must be multiplied to obtain maximum range over land.

TABLE 2B-III	
FACTOR FOR MAXIMUM RANGE OVER LAND	
Wavelength (cm)	R_{max} (land) / R_{max} (sea)
10	1.00
25	0.94
35	0.89
45	0.84
70	0.71

For the recommended 70-cm radar, the maximum range over land becomes just equal to the horizon range at 20,000 feet, and is therefore adequate. The 70-cm radar in the APS-20B radome recommended for 1957 has a maximum range of 100 miles. It is therefore of marginal utility over land from the standpoint of maximum range only. The S-band stacked-beam radar recommended for height finding and as an adjunct of the UHF in the later period outperforms the UHF radar over land in this respect, with a maximum range of 220 miles.

Clutter Spectra and MTI Improvement

The performance of AEW radars over land can not be predicted with any great degree of confidence because of the lack of information on the properties of land clutter. There have been some measurements made of σ_o (the average cross section per unit area) at X-band, but none at wavelengths useful for AEW. Data from various sources vary widely. Figure 2B-7, which summarizes the available data on σ_o at X-band, shows variations of 15 db in measured values of σ_o under supposedly similar conditions. There is no reliable information on the variation of σ_o with angle of incidence, wavelength and terrain. It is not even certain that the land return is sufficiently homogeneous to make the concept of an average cross section per unit area a useful one for AEW calculations. Certainly at X-band and especially over terrain with many cultural landmarks, the land clutter is so inhomogeneous (for the resolutions characteristic of small airborne radars at this wavelength) that these radars are useful for mapping, navigation and bombing.

It is obviously impractical to make radar-performance predictions over land as was done in the over-sea case. It is possible, however, to make diagrams that display

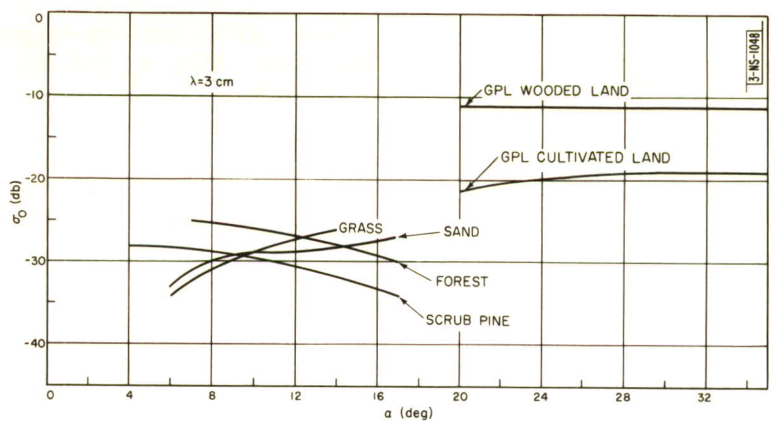


Fig. 2B-7. σ_0-normalized backscatter coefficient for land. (Philco Corporation and General Precision Laboratories.)

the dependence of clutter-to-target ratio on wavelength and antenna size, σ_0 being set at a reference level of 0 db. A set of such diagrams was constructed in the following way.

It was assumed that there is no variation of σ_0 with angle of incidence; hence σ_0 does not vary with range. Then the clutter-to-target ratio is given by

$$\frac{C}{T} = \frac{\sigma_0 \, c \, \tau \, \theta_H R}{2\sigma} f\left(\frac{\sigma T}{f_r}\right) , \tag{1}$$

where $f(\sigma T/f_r)$ is the improvement factor when single-delay or double-delay MTI is used. All other quantities were previously defined.

Under the assumptions made, it is clear that clutter-to-target ratio increases directly with range, as contrasted to the behavior of clutter-to-target ratio over the sea.

The total clutter width is calculated as before, except that the inherent clutter width σ_L is

$$\sigma_L \text{ (cps)} = 50/\lambda \quad .$$

Figure 2B-8 shows contours of constant clutter-to-target ratio under these conditions: $\sigma_0 = 0$, $R = 100$ miles, $\tau = 1$ μsec, $f_r = 300$ pps, $\sigma = 2\ m^2$; double-delay MTI is applied. Clutter-to-target ratios for other ranges, pulse durations and target cross sections can readily be computed by adding or subtracting one db for every db change in these parameters from their reference values, in accordance with Eq.(1) above.

Figure 2B-9 displays the same information, except that it is assumed that the scanning contribution to the clutter spectrum has been eliminated by means of an azimuth

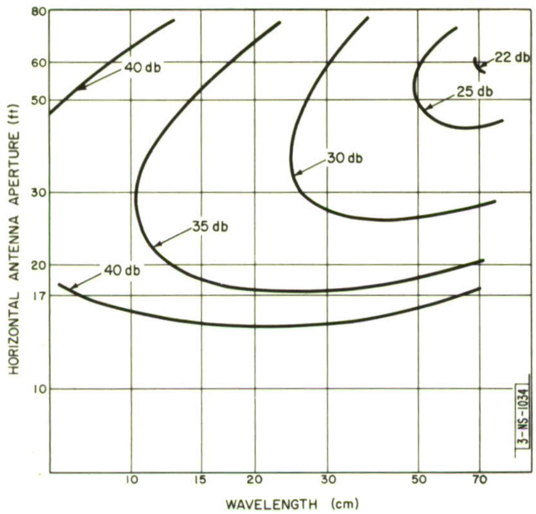


Fig.2B-8. AEW clutter-to-target ratio (land). Double-delay MTI, σ_o = 0 db, range = 100 nautical miles.

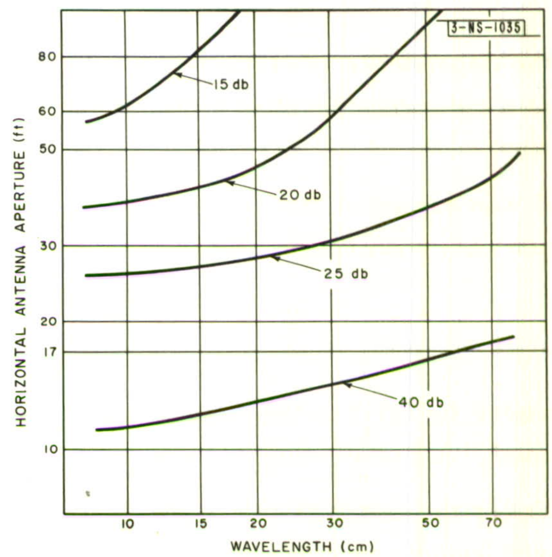


Fig.2B-9. AEW clutter-to-target ratio (land). Double-delay MTI with 35-db cancellation limit; step scan to remove scanning clutter; σ_o = 0 db, range = 100 nautical miles.

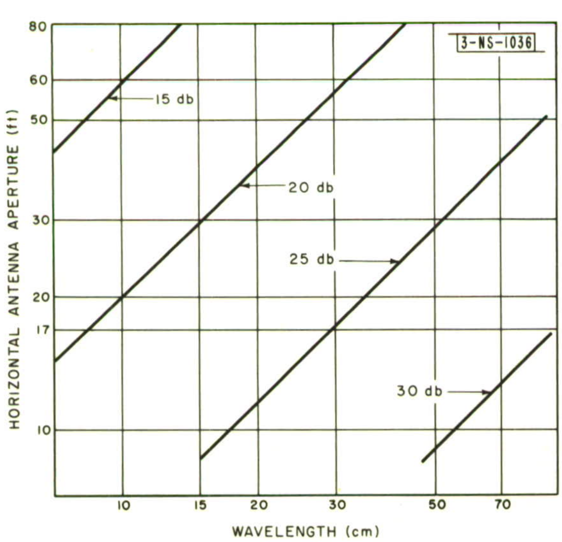


Fig.2B-10. AEW clutter-to-target ratio (land). Double-delay MTI with 35-db cancellation limit; step scan to remove scanning clutter and displaced antennas to remove velocity clutter; σ_o = 0 db, range = 100 nautical miles.

step scan. This method of scanning was considered because of the large clutter-to-target ratios that remain even after application of double-delay MTI, as can be seen from Fig. 2B-8. An upper limit of 35-db cancellation was assumed, because of the engineering difficulties involved in obtaining components that are linear, stable and matched. This 35-db limit is included in the contours of Fig. 2B-9.

Still another method for reducing clutter is to eliminate the platform-motion spectrum component by the displaced-phase-center technique. Figure 2B-10 shows the clutter-to-target ratios after this technique has been applied in addition to step scanning and double-delay MTI, but with the 35-db cancellation limit still in effect.

It is evident, from examination of these diagrams, that little improvement results from the application of these spectrum-narrowing techniques, when the 35-db cancellation limit is assumed. Research is needed on both techniques, and the engineering limits on cancellation ratio should be pushed back as far as possible by intensive development. In addition, many measurements of clutter must be made before any confidence can be placed in predictions of AEW radar performance over land.

D. J. Crowley, Jr.
J. W. Coltman

REFERENCE

1. Philco Corporation Research Division, Philadelphia, Pa., Final Report on First Portion of Philco Tasks under Project Lincoln, Subcontract No.8 (Philco Corp.), Prime Contract AF-19(122)-458(MIT), July 31, 1953.

APPENDIX 2-C

HEIGHT FINDING IN AEW

INTRODUCTION

In the combat zone, height data are necessary in order that interceptors can accomplish radar lock-on, as has been shown in Appendix 2-A. In the data zone outside the combat zone, height data are less important, although desirable as an aid to earlier raid-size assessment. The purpose of operating AEW aircraft is to obtain radar detection of enemy bombers at both low and high altitudes. It would be desirable to obtain height data as well as position data on all targets within horizon range of the AEW aircraft, but this does not appear to be possible because sea clutter will limit the short-range and low-altitude coverage, as will be explained in this appendix. However, the free-space range of the height finder should be 180 nautical miles if the AEW aircraft is to operate at 20,000 feet.

The two solutions to the height-finding problem that are suggested are a nodding-beam height finder, as the immediate solution, and a stacked-beam height finder as a more nearly adequate but longer-term solution.

NODDING-BEAM HEIGHT FINDER

The suggested nodding-beam height finder could be fitted to the RC-121 or WV-2 aircraft as a modification. The existing APS-45 nodding-beam height finder in these aircraft is limited in its range performance, being able to find height on aircraft targets out to ranges of about 75 miles. Using the parameters of the APS-45, a range of 75 miles is calculated on a 2-m^2 target. The parameters to be suggested give a calculated range of 180 miles on a 2-m^2 target. A high prf mode is also suggested for raid-size analysis by A-scope observation and aural listening.

The new parameters are listed in Table 2C-I, with the APS-45 parameters given for comparison.

The most difficult change to make is the antenna size, but this is also the most important factor in obtaining increased range. Aerodynamic calculations show that a radome large enough to accommodate the 8-foot vertical by 5-foot horizontal aperture could be mounted on top of the WV-2 aircraft, in place of the radome that now houses the $7\frac{1}{2}$-foot vertical by 2-foot horizontal aperture antenna, without seriously degrading aircraft performance.

The frequency was chosen for several reasons. When observing targets at long range, effects of atmospheric attenuation are important. At X-band, weather effects are very

TABLE 2C-I		
PARAMETERS OF NODDING-BEAM HEIGHT FINDERS		
	AN/APS-45	Suggested
Antenna size (ft)	7-1/2 × 2	8 × 5
Frequency (Mcps)	9300 (X-band)	5600 (C-band)
Antenna gain (db)	38.5	38.5
Peak power (kw)	450	2000, 1000
Pulse length (μsec)	2	2, 1/2
Pulse rate (pps)	450	300, 2000
Average power (w)	400	200
Nod rate (deg/sec)	14	7
Hits/scan (nodding)	30	60
Receiver noise figure (db)	13	11
Range on 2-m^2 target (n. mi.)	75	180

noticeable at 100-mile range. Even at the suggested frequency of 5600 Mcps (C-band), weather attenuation and cloud clutter will be noticeable, but less so than at X-band. The reason for choice of C-band instead of S-band is that a nodding-beam height finder must have a narrow vertical beamwidth, both for accuracy of height finding and to keep the beam off the water when measuring height on low-flying targets.

Another reason for choice of C-band is that a magnetron is available in this frequency band which will give 2 Mw peak power output. The higher power is an important factor in obtaining the increased range. Such high power would be very difficult to handle at X-band, both in the waveguide and in the antenna.

Although the horizontal and vertical beamwidths are larger than those that would be obtained at X-band, and hence the antenna gain is 45 db lower than it could have been at 3 cm, the combination of (1) higher power available, (2) less weather effect, (3) more pulses per scan, and (4) better receiver noise figure, makes C-band performance markedly superior. In addition, the larger horizontal aperture of the suggested new antenna would cause the X-band horizontal beamwidth to be very small (about 1.6°) and would cause difficulty in pointing the height finder in the direction of a target found on the search radar.

The limitation imposed by sea clutter can be explained by Fig. 2C-1. A low-flying aircraft target can be obscured by sea clutter backscattered from the area below

the target. The target has to compete with the clutter from an area of sea one pulse-length long and one horizontal beamwidth wide at the range of the target. A certain vertical angle ϕ is formed at the radar antenna between the direction of the target and the direction of the illuminated patch of sea. The angle ϕ is directly proportional to the target altitude, but essentially independent of radar altitude. The magnitude of the return from the patch of sea is determined by the area of the patch, by the range from the radar, by the position of the patch in the radar beam, and by the reflectivity σ_0 of the patch. The reflectivity σ_0 is a function of sea conditions, the radar frequency, and the angle of incidence of radar illumination. The intensity of the target which competes with the sea return is determined by the effective target area, the range from the radar, and the position of the target in the radar beam.

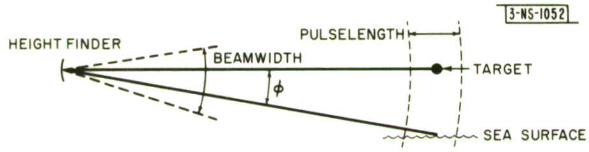


Fig. 2C-1. Determination of target-to-clutter ratio.

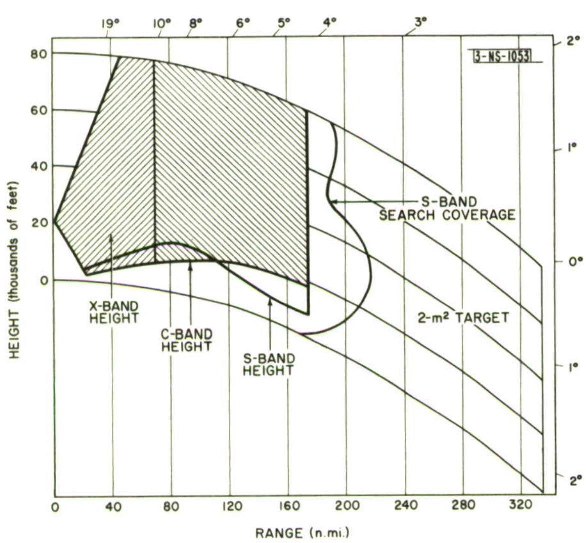


Fig. 2C-2. Vertical coverage diagrams for height finders over rough sea.

To work out a specific example, assume that the target is at 160-mile range, and that a C-band height finder is used, with an 8 × 5 foot antenna. The area of sea illuminated by the radar beamwidth and pulselength is 3.0×10^6 m^2. With the radar at 20,000 feet, the angle of incidence at 160 miles is 0.005 radian, and the corresponding σ_0 for C-band is −42 db for rough sea. The effective scattering cross section of the illuminated area of sea is then 145 m^2. A signal from a target with this effective area located just above the sea would be equal to the sea clutter. A 2-m^2 target would give a return 20 db smaller than the sea clutter. In order to be visible in the sea clutter, a 2-m^2 target would have to be located at an altitude high enough that, when the beam is pointing at the target, the antenna gain in the direction of the sea clutter is 10.5 db down, or the two-way gain is 20 db down. This determines the minimum angle ϕ in Fig. 2C-1. For the 8-foot vertical aperture in C-band, the vertical beamwidth is 1.45°, and ϕ is 1.05°. The corresponding target altitude is 18,000 feet. Thus the 2-m^2 target would be visible at

any altitude above 18,000 feet at 160 miles. A similar calculation shows that this target would be visible above 12,500 feet at 100 miles. Lower targets can be seen when the sea is less rough.

The fact that the target is high enough to be visible on the range-height indicator over rough sea does not necessarily mean that an accurate measurement of altitude can be made. In the absence of sea clutter, a fluctuating target paints a vertical line of fluctuating length on the indicator. The operator estimates the center of the line to determine height. Only the upper half of the vertical line will show above the sea clutter on targets at the minimum altitudes mentioned above. Without knowing the length of the line, the operator cannot estimate its center. Fortunately, however, the operator can see the whole vertical line if he waits until a particularly good "blip" is obtained, but this may require a wait of several seconds.

With these limitations in mind, Fig. 2C-2 shows the vertical coverage that will be obtained using the C-band height finder.

STACKED-BEAM HEIGHT FINDER

The suggested stacked-beam height finder is to be used with the top-mounted 30 × 8 foot UHF AEW radar. It can be used in the same radome, either back-to-back with the search antenna or multiplexed in the same antenna. The stacked-beam height finder provides simultaneous search and height finding, and hence is an important adjunct to the UHF search radar, providing important operational advantages. The suggested frequencies for the large-radome AEW aircraft are 425 and 2880 Mcps. Both radars should be tunable. This frequency diversity provides considerable resistance against ECM. For instance, the height finder can be allowed to operate on standby until a target is observed on the UHF radar. The height finder can then be switched on just before the next look at the target. It provides range, azimuth, and elevation in one look. In the event that the enemy desires to use electronic jamming against the search aircraft, the quick look with the height finder, on a different frequency, can make it very difficult for him to find the new frequency, tune his jammer to it, and turn the jammer on before a range and height fix has been obtained. An additional advantage of using two frequencies for search is that the MTI blind-speed areas on the PPI will be filled in, except for the points of zero relative velocity.

The stacked-beam system gives 3 target coordinates in each look. This is most important when automatic means are used for reporting target output from the radar. For instance, the computer can record height data while it is determining the azimuth and

range of the target. It can then look back at the height data recorded at the best azimuth position, or it can average the height data over the best hits obtained when the beam was scanned past the target.

The principle of the stacked-beam height finder is explained in Fig. 2C-3, which is a rectangular plot of one-way gain, vs elevation angle for two antenna lobes that have been displaced to cross over at −2 db. The straight line is a plot of the difference between the two lobes, which is zero at the cross-over. A separate receiver is used for each lobe and, if logarithmic IF amplifiers are used, the video outputs may be subtracted to give pulses of amplitude directly proportional to the angle the target is off the cross-over. The "db difference" line is straight all the way between the outside 2-db points on the two lobes. Interpolation between two lobes is possible, therefore, over a vertical angular range of 1.65 times one beamwidth, if the cross-over is set at 2 db. Each additional lobe adds one-half this amount to the vertical coverage. The two lobes described in Fig. 2C-3 were of equal gain and were connected to receivers of equal sensitivity.

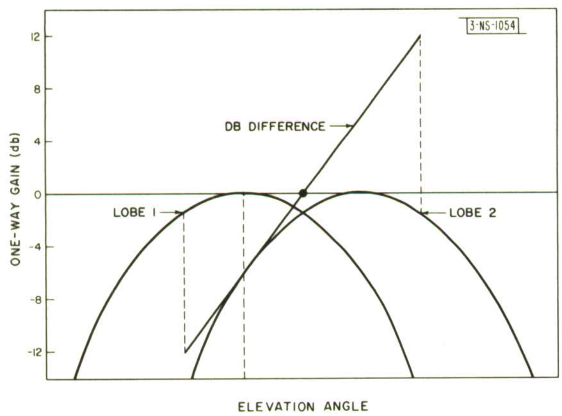


Fig. 2C-3. Two lobes of a stacked-beam height finder.

Nothing has been said yet about how the target is illuminated. Of course, the transmitter power could be split equally between the two lobes, and this is often done, but lobes above the first two are used only to provide high-altitude coverage at shorter ranges, and the power in the upper lobes can be drastically reduced. Separate duplexers are used on the several feeds generating the lobes, so that full receiving gain can be used on each of the lobes, making possible direct angular interpolation between lobes. The vertical search-coverage diagram can be drawn considering each lobe separately between cross-overs, using the actual transmitter power that has been split off for each particular lobe. If the outputs of all the lobes were combined and put on one PPI indicator, then a signal predominately in one lobe would have to compete against noise from its receiver and all the other receivers. However, the high lobes are used only for short ranges, and the video from successive receivers can be shut off during the range sweep. The long-range coverage provided by the lowest lobe is, therefore, not compromised by noise from the other receivers.

Determination of the vertical coverage for height finding involves some assumptions about the use technique. In the discussion that follows, it will be assumed that the target is first detected, as described, on a PPI indicator or by means of a digital computer. Then the height of the target is determined by interpolation between lobes.

As shown in Fig. 2C-3, a target at the outside –2 db point on one lobe is at the –14 db point on the other lobe. This is the extreme lower limit of height interpolation. A target large enough to give echoes that exceed noise 50 per cent of the time in the stronger lobe will exceed noise a much smaller percentage of the time in the weaker lobe. This target must be 12 db stronger if it is to exceed noise 50 per cent of the time in the lower lobe. Two kinds of experimental evidence are available on target fluctuations. The first is a statistical plot of echo amplitude on a jet aircraft, shown in Fig. 2C-4. The relative target area is shown to exceed 0.1 times its peak area 50 per cent of the time. If this level which is exceeded 50 per cent of the time is called the median level, the target is 8.5 db above this median level 10 per cent of the time. If we can find height on a target that exceeds noise 10 per cent of the time in the weaker lobe, we can find height on the 2-m^2 target at ranges where the target is 3.5 db (12 db – 8.5 db) stronger than 50 per cent blip-scan. This is 93 per cent of the range at which it will be detectable at the –2 db point in the stronger lobe. To give good height data, the target echo must exceed the noise; and, to exceed noise by another 3 db, the range would be reduced to 65 per cent. The target located at the point discussed so far is at the worst place, the limit of interpolation. Targets near the cross-over between lobes will exceed noise in both lobes a larger percentage of the time.

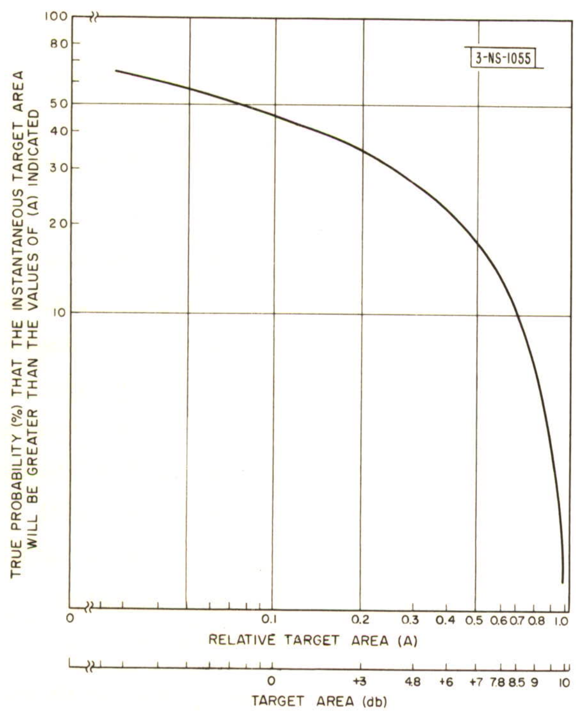


Fig. 2C-4. Probability distribution of target area.

The second kind of experimental evidence has been obtained with actual stacked-beam height-finding experiments on jet aircraft targets, which shows that the height-finding coverage is between 80 and 85 per cent of the detection coverage of the radar.

The maximum detection range of the recommended height finder is 220 miles. Height-finding range is 80 per cent of this, or 175 miles.

The performance of the stacked-beam height finder against sea clutter can be calculated in the same way as for the nodding-beam height finder. On the RHI indicator, all targets below the lower 2-db point on the lowest lobe are displayed at the elevation angle of that point, regardless of the strength of the target. Sea clutter will show as a band at the elevation angle of the lower 2-db point. An aircraft target near the sea will be displayed as a vertical line extending out of the clutter line. Because the aircraft is a scintillating target, at times a bright spot will appear at the true altitude of the aircraft, when the aircraft echo is strongest. This spot will be more easily visible on the stacked-beam RHI than it would be on a nodding-beam RHI because, in the stacked-beam case, sea clutter is not allowed to paint on the persistent phosphor at the altitude of the target.

As a specific example of minimum target altitude for height finding over rough sea, assume a range of 160 miles, S-band, 30×8 foot antenna, and a 2-m^2 target. Calculated in the same way as previously for the C-band nodding-beam case, σ_0 for rough sea is -55 db, the illuminated area of sea is 10^6 m^2, and the effective echoing sea area is 7 m^2, which is about 6 db stronger than a 2-m^2 target. The tilt can be adjusted to place the lower 3-db point of the lobe on the water (about $-1°$ tilt), and a 2-m^2 target will be detectable at 160-mile range if it is at the center of the lobe, which will then be at 20,000 feet altitude; altitude may be determined on targets flying at 20,000 feet and above. With this same tilt setting, altitude can be determined on targets flying as low as 3000 feet (the lower 2-db point) when sea clutter is not present.

The vertical coverage obtainable with 4 lobes in a stacked-beam height finder with an 8-foot vertical aperture on S-band is shown in Fig. 2C-2. The parameters of the recommended height finder are given in Table 2C-II.

The accuracy of height determination by the two suggested height finders is comparable, and is sufficient to fulfill the requirements set forth in Appendix 2-A. The nodding-beam height finder should be able to report targets to within 1/7 of a beamwidth at 160-mile range, or to about 0.2°. To this must be added the error in knowledge of the vertical, which can and should be made very small, and the error in the indicating system. Over-all accuracy of ± 5000 feet should thus be possible on targets high enough to be clear of clutter, as previously explained. The stacked-beam height finder also should report targets to about 0.2°, based on results of tests with stacked-beam systems using a beamwidth equal to that recommended. With the same vertical

TABLE 2C-II	
PARAMETERS OF RECOMMENDED HEIGHT FINDER	
Frequency (Mcps)	3000
Antenna size (ft)	30 × 8
Antenna gain (db)	41
Peak power No. 1 lobe (lowest) (Mw)	2.5
No. 2 lobe	1.25
No. 3 lobe	0.62
No. 4 lobe (highest)	0.62
Receiver noise figure (db)	8
Rotation rate (rpm)	6
Pulse rate (pps)	300
Hits/beamwidth	7
Coverage (see Fig. 2C-2*)	

and indicator error, over-all accuracy of ± 5000 feet should also be obtained from the stacked-beam system.

EFFECT OF SPECULAR REFLECTION

Both the nodding-beam and the stacked-beam height finders will be affected by specular reflection from the surface of the sea. The effect should not be serious, however, with either type of height finder. When the sea is very smooth, specular reflection off the water will cause an image target apparently to be as far below the sea surface as the real target is above the surface. Three effects combine to reduce the amplitude of the reflected target:

> At the high frequencies used, even the smoothest sea will cause at least 6 db attenuation of the reflection. The direct signal will predominate and, if the sea is at all choppy, there will be no reflection at all. This is why no effect of specular reflection was taken into account in calculating maximum detection range.

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*It is within the capabilities of presently available components to increase the pulselength from 1 to 2 μsec and thereby increase the maximum range from 220 to 260 nautical miles. This was not done here for two reasons: (1) to retain range resolution for raid-size assessment, and (2) to avoid difficulty with height finding in the presence of specular reflection from very smooth sea.

With the antenna pointed at the target, the beamwidth is narrow enough to reduce sea clutter originating directly under the target. The two-way antenna gain is even lower in the direction of the specularly reflected echo, and would make the image target negligible even if specular reflection were perfect. (Antenna stabilization with an accuracy of 1/4 beamwidth is required to take advantage of the vertical antenna pattern. This stabilization need only be maintained during level flight if loss of data during aircraft turns can be tolerated. The RHI indicator must be data-stabilized, of course.)

Echo pulses from the sea surface will arrive at a later time than the direct echo from the target. In fact, for each transmitted pulse, three echoes will be received from a single target: the two-way direct echo, the echo from direct transmission but reflection from the sea on return, and the echo received involving two-way reflection from the sea. The order of reception will be the order in which they were listed. Two things can be said about these delayed echoes, applicable to either nodding-beam or stacked-beam height finding. The first is that short transmitted pulselengths serve to cause reflected pulses to remain separate from the direct-echo pulses. A 1-μsec or longer delay between leading edges of the echo pulses will be observed if the target is at an altitude of 12,000 feet or more at 100 miles. The stacked-beam height finder will report the first echo at its true altitude and the two other echoes as being on the sea. The nodding-beam height finder will report the first echo at its true altitude and the other two echoes as being under the sea. These extra echoes will be observed only if the sea is smooth enough to give no clutter and good specular reflection.

J. L. Shultz

APPENDIX 2-D
BLIND-SPEED PATTERNS IN MTI RADAR

The application of delay-and-subtract or double-delay-and-subtract MTI to a radar gives rise to blind target speeds at which the radar is totally inoperative, surrounded by regions of velocity for which the signal strength is reduced. In these regions, the maximum range of the radar (set by receiver noise) is reduced while the minimum range (which may in many cases be set by clutter) is increased, so that over certain finite velocity bands the radar cannot see the target. For a target holding a constant velocity course through a search area, the effect gives rise to discrete areas of sensitivity, whose shapes are calculated in this appendix.

Figure 2D-1 shows curves of ratio of clutter-plus-noise to noise as a function of range, calculated for an L-band radar with a 30-foot antenna, 0.5-μsec pulse and 10-Mw peak power. Curve I shows sea clutter alone, Curve 2 the reduced clutter due to application of single-delay MTI, and Curves 3 and 4 the further reduced clutter obtained with double-delay MTI, for the cases of looking broadside and along the line of motion, respectively. The signal returned from a 2-m^2 target is shown as the straight line (5). For any given radial target velocity V_R, this target signal will be reduced by a factor $\sin^2(\pi V_R/V_B)$ for single delay and $\sin^4(\pi V_T/V_B)$ for double delay, where V_B is the first blind-velocity characteristic of the repetition rate and wavelength of the radar, namely $V_B = f/2$. The reduction will shift the target curve of Fig. 2D-1 downward, so that new intersections with the noise (0-db) line and the clutter curve will determine new maximum and minimum ranges for each radial velocity.

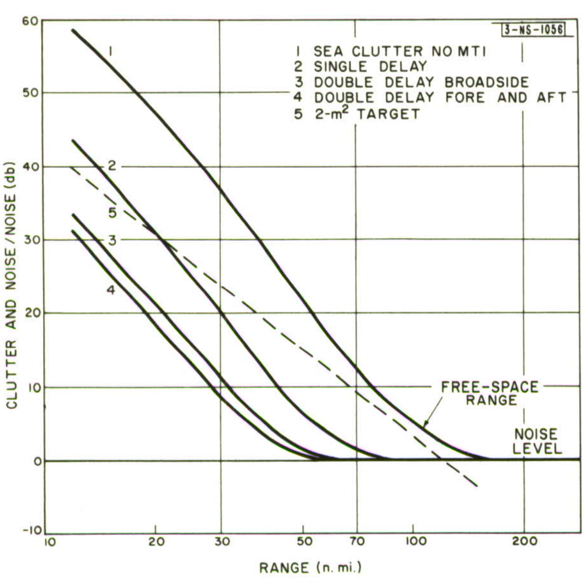

Fig. 2D-1. Sea-clutter curves for L-band radar.

The effect of this degradation on the radar may manifest itself in several ways. One way to estimate the effect is to plot a representation, as on a PPI course across the field at a particular velocity.

The radial velocity of a target toward a radar will be simply $V_r = V_T \sin\theta$, where θ is the bearing of the target measured from the normal to the course of the target.

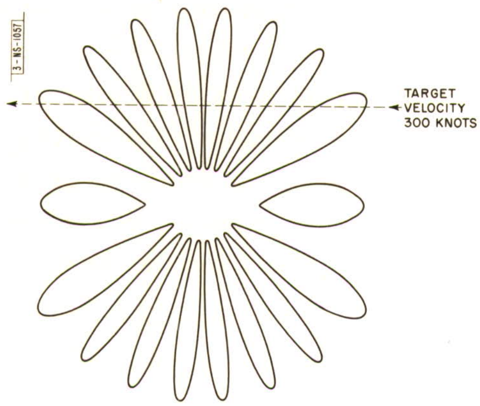

Fig.2D-2. L-band radar, 30-foot antenna, single-delay MTI, clutter limit included.

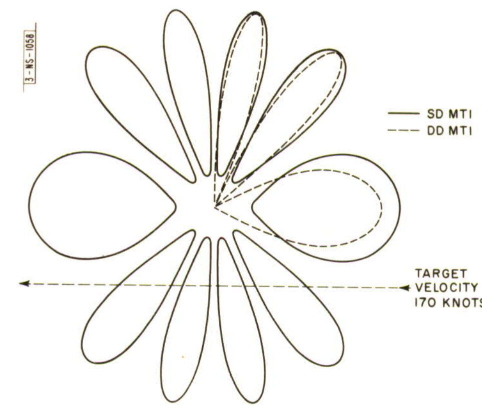

Fig.2D-3. L-band radar, 30-foot antenna, double-delay MTI, clutter limit included.

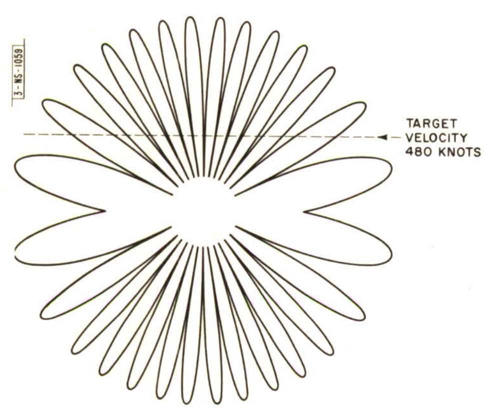

Fig.2D-4. L-band radar, double-delay MTI, f = 300 pps.

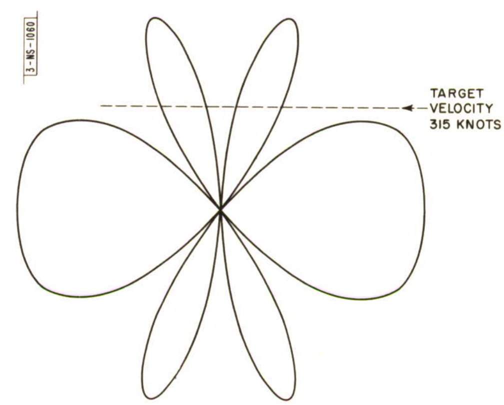

Fig.2D-5. Normal crossing of AEW line. UHF radar, double-delay MTI, f = 300 pps.

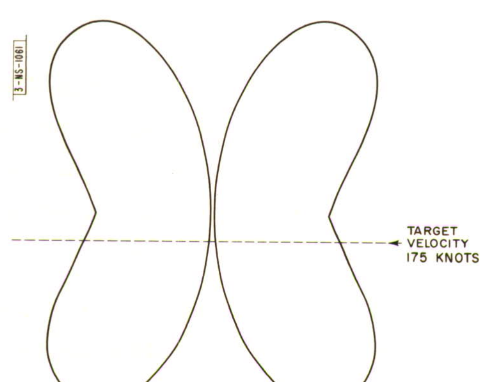

Fig.2D-6. UHF radar, double-delay MTI, f = 300 pps.

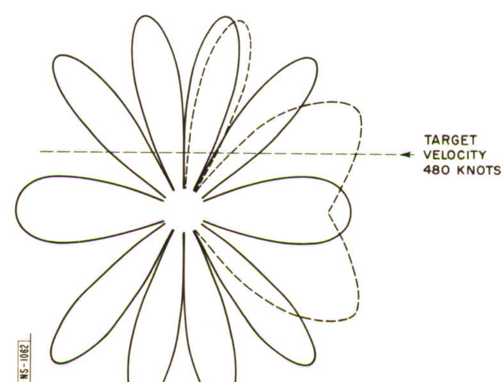

Fig.2D-7. UHF radar, f_1 = 300 pps, f_2 = 380 pps.

Thus the sensitivity patterns for a given course will be functions of θ only, and not of the separation of the course line from the radar, and the patterns will be correct for a family of parallel courses. When the radar is moving, as in an AEW aircraft, the situation is not much different. The radial component of the radar velocity ($V_A \cos\theta$) can be ignored because the Doppler is always compared with that from the ground at the angle of the beam so that the effective radial velocity becomes $V_T \cos(\phi - \theta)$, where ϕ is the angle of crossing of the AEW track, and θ the bearing from the AEW.

Figure 2D-2 shows a plot of the active regions for the L-band radar and a 300-knot target calculated from the data of Fig. 2D-1. The clutter occupies the central region; between the lobes, the clutter extends outward and the receiver noise inward (relative to the target) to "pinch off" the active regions.

Figure 2D-3 is a similar plot showing a target velocity of 170 knots. The reduction in number of lobes is evident. The dotted lines in one quadrant show the pattern for double-delay MTI; here clutter is overcome all the way to zero range for most velocities, at the expense of a slight degradation in the width of the lobes. Figure 2D-4 is illustrative of higher-velocity targets, giving many more lobes. This is for double-delay MTI, and the effect of clutter (small, in this case) has been ignored. Figures 2D-5, 2D-6 and 2D-7 are for a UHF radar; the small numbers of lobes and wide insensitive areas are very apparent.

The following calculations have been made under the assumption that the target signal consists of a single frequency. For propeller-driven aircraft, an appreciable factor of the returned power is spread over a wide spectrum of propeller harmonics, and the nulls will be much less well marked than in the diagrams. Jet aircraft, however, return signals with very narrow spectra, and for these the diagrams may be expected to apply essentially as drawn.

One way to fill in the insensitive areas is to vary the repetition rate; in Fig. 2D-7, the dotted lines are drawn for a repetition rate changed from 300 to 380 pps, showing how the gaps are filled in for this particular target velocity. Similar results can be obtained by changing the radar frequency. The zero-velocity gap normal to the target will, of course, be invariant with these changes and in general cannot be avoided.

In many cases, MTI is necessary only for short ranges, beyond which clutter is not strong enough to interfere with target detection. In this event, the MTI can be automatically gated out beyond a selected range, so that the coverage becomes unaffected by blind speeds in this outer area.

J. W. Coltman

CHAPTER 3

AIRCRAFT-INTERCEPT AND FIRE-CONTROL RADARS

CHAPTER 3

AIRCRAFT-INTERCEPT AND FIRE-CONTROL RADARS

INTRODUCTION

The sequence of operations involved in detecting, identifying, intercepting and finally killing an enemy aircraft is in general one that involves cooperation between two or more radars, as well as among many other components of a system; it is for this reason that it is impossible to discuss the performance of an aircraft-intercept and fire-control radar in absolute terms. The performance of the AI radar complements that of both the vectoring radar and the armament; improvements in the performance of any one relax the requirements on the other two. As a corollary, it can be said that, associated with the present-day development of vectoring radars and armament, there exists a minimum performance specification that AI radars must exceed. Following this reasoning, it appears that the introduction to a discussion of AI radars must contain the answers to the two questions: What performance in AI radars is acceptable? Do existing AI radars attain this standard of acceptance?

The determination of acceptable performance of an AI radar with respect to the vectoring radar and armament is a project of considerable magnitude, involving either extensive flight tests or elaborate simulation. Further, for any solution to have meaning, all the parameters of the situation should be stated with it. Nevertheless, a simple answer – applicable with moderate accuracy to an average situation that includes both land-based and airborne-vectoring radars – is essential to this discussion, and an attempt has been made to draw this type of solution from data supplied by the Bell Telephone Laboratories;[1,2] a discussion of some of their results will be found in Appendix 2-A. Of the various parameters defining the performance of the AI radar, lock-on range is the most critically important in determining the success of an attack; other parameters such as beamwidth, range discrimination and data rate are important but secondary. It is convenient that beyond a certain lock-on range the probability of interception becomes insensitive to many of the parameters of the vectoring radar and of the armament; it is this range that can be quoted as defining satisfactory performance. On this basis, it can be concluded from the BTL studies that a head-on attack on a B-47 by a 600-knot interceptor armed with rockets can be made successfully if there is a 50 per cent cumulative probability of lock-on at a range of 10 miles. When the interceptor is armed with guided missiles, it appears that the probability of a successful attack is very small if the 50 per cent probability of lock-on occurs at 8 miles, moderately high at 10 miles, and approaches certainty when the cumulative probability has reached 50 per cent at 15 miles. safe?

Recent information indicates that bombers such as the B-47 are capable of carrying out at least half of a long-distance mission at altitudes less than 1000 feet; for this reason, it no longer seems possible to argue that at low levels the target should be a propeller-driven aircraft and that a different speed and target cross section should be used in determining the required low-level performance of an AI radar. The required lock-on ranges are reduced slightly only because of the greater maneuverability of the interceptor when at low altitude. For these reasons, it is concluded that at all altitudes the AI radar will give satisfactory performance if the 50 per cent cumulative probability of lock-on is 10 miles on a B-47 target when the interceptor is armed with rockets, and 15 miles for an interceptor armed with guided missiles. A list of AI radars together with some of their characteristics is given as Appendix 3-A.

It is not possible to make simple unequivocal statements concerning the lock-on range of modern AI radars. Measurements have been made using propeller-driven fighters and bombers and using jet fighters as targets, but information on jet-bomber targets is non-existent. Further, most measurements have been made at altitudes so great that clutter is of little importance. In the measurement of lock-on range, the operator first detects the target, then locks the radar to it by pointing the antenna and adjusting a range gate; thus the judgment of the operator and the extent to which his judgment is assisted by an a priori knowledge of the target position also enters into the measurement. Motion studies have shown that an average operator can perform the operations of locking-on in an average time of 12 seconds. Thus it might be expected that at any closing speed the lock-on range could be calculated from the much more determinable detection range by subtracting a distance corresponding to 12 seconds. But, according to a study made by R. S. Sargent at the Bureau of Aeronautics[3] this is not the case; time differences calculated from the difference between the detection and the lock-on ranges in his study vary between limits of 30 and 70 seconds.

The detection range of an AI radar is subject only to the normal vagaries of radar measurements; it is certainly greater than the lock-on range. Table 3-I presents information on detection ranges collected from a number of sources. It is probable that the target cross sections of jet bombers will be about twice those of the fighters, and hence detection ranges about 20 per cent greater than those shown in the table can be expected on bombers.

The lock-on ranges measured at Patuxent are roughly one-half the detection ranges listed in Table 3-I. Recent measurements made by the Westinghouse Electric Corporation on an APQ-50 radar flown at an altitude of 10,000 feet indicate a detection range

TABLE 3-I DETECTION RANGES OF AI RADARS						
Origin of data	Patuxent			Hughes	Westinghouse	British
Radar	E-10			E-5	APQ-50	APS-21
Target	Jet fighter			Prop. bomber	F8F, FM2	Jet fighter
Terrain	Land		Ocean	?	Ocean	Land & ocean
Closing speed (knots)	610	400	800	600	300	500
Altitude (ft)	Range (n. mi.) at 50 per cent Probability of Detection					
40,000	19		14			
20,000				18 – 25		
10,000					18.7	
5,000	7.5	8.5	14			
1,500						3.8
500						1.5

of 18.7 miles and a lock-on range of 16.5 miles. A discussion with engineers from Hughes Aircraft Company led to the belief that the degradation in lock-on range over detection range, which is exhibited in the Patuxent data, probably represents the manner in which the data were collected and not the best obtainable performance. It has been concluded that, in comparison with the demands to be made on AI radars, their performance is tolerable against targets flying at 10,000 feet or higher. The same conclusion cannot be drawn about the performance of the radar at target altitudes less than 10,000 feet. At 5000 feet over land and (presumably) over rough water, the detection range is inadequate for any type of mission; the table shows that this unsatisfactory situation very rapidly becomes worse at altitudes less than 5000 feet.

NOTS

The remarks of the preceding paragraphs can be summarized as follows:

> The lock-on range required of an AI radar is determined by parameters that depend upon the weapons system as a whole, but significant average figures can be quoted: an interceptor armed with rockets has a high probability of completing its mission if the radar has a 50 per cent cumulative probability of lock-on at a range of 10 miles; the required range is 15 miles if the interceptor is armed with missiles.
>
> At altitudes in excess of 10,000 feet, the lock-on ranges of existing AI radars are tolerable.

Below 5000 feet, the ranges are clearly inadequate, and their inadequacy becomes progressively more marked as the altitude decreases.

DELAY-LINE MTI ADDED TO AI RADARS

The lock-on range of an AI radar is related to its detection range, and it is the latter around which this discussion centers. At the outset, it should be noted that the manufacturers of AI radars are aware of the necessity of reducing the interval between detection and lock-on; Hughes Aircraft Company, for example, is investigating methods of reducing the motions made by the operator in performing the lock-on function, and many company representatives have discussed methods and plans for automatic lock-on.

The problem of obtaining adequate detection ranges at low altitude is the problem of seeing signals in the midst of land or sea clutter. In general, clutter may find its way into the radar by way of sidelobes located in the neighborhood of 90° from the main axis of the beam of the radar, by way of all the other sidelobes, and by way of the main beam when the main beam touches the land or water. The relative importance of each of these three paths is discussed in Appendix 3-B; the general conclusion is that, if the power at the peak of the first sidelobes is more than 15 db below the power in the main beam, it is improbable that sidelobe clutter is of much importance except for that clutter which enters through sidelobes near the 90° position and which is responsible for the altitude line. Simple calculations show that the observed ranges of AI radars at low altitudes can be explained on the assumption that the clutter limiting the performance of the set is that which enters by way of the main beam.

There is little information available concerning the sidelobe levels associated with the antennas of the current AI radars. It is known that, because of the presence of a radome and of the metal parts of the aircraft that surround the antenna, the pattern of an antenna in an aircraft may depart markedly from the pattern obtained in the laboratory. A study of the sidelobe levels associated with the antenna *in situ* is needed and should be made.

Artificial dielectrics from which good lens antennas can be constructed have become available during recent years; further, a development program at Hughes has shown the possibility of constructing X- and S-band, scanning, slot antennas. Both lens and slot antennas are superior to mirrors in several respects: in both cases the aperture illumination is under much closer control, and in both cases the primary feed can be hidden so that stray radiation from it cannot contribute to the radiation pattern and, in

particular, to the sidelobes which are responsible for the altitude line. Support for study programs on both types of antennas is recommended. In the case of the lens antenna, a study is required of the aberrations introduced by the various types of scanning and of the contours of lenses that would serve to minimize such aberrations.

It is intended in this section to examine the problem of fitting delay-line MTI to conventional pulsed radars and, from this examination, to draw conclusions concerning the proper trend in future designs. The independent variables of the problem are the target-to-clutter ratio and the widths of the clutter spectra with which the radar has to deal. Fundamental measurements from which these variables can be calculated are few and have been made for specific purposes; thus, the measurements are not rigidly controlled and the results not always comparable. For these reasons, the reader is warned that the results of these calculations are statistical rather than exact: radars that are found here to be unsatisfactory will, in fact, under some circumstances prove very satisfactory; radars that are useless at low altitude on a 2-m^2 target over rough sea may be very useful over smooth land at moderate altitudes on a 12-m^2 target. The calculations here have been made and the conclusions drawn for small, 2-m^2 targets flying over rough seas and level wooded land; the results apply only to specific radars whose pulselengths, repetition rates, and other parameters have been fixed so as to demonstrate the effect of varying wavelength and antenna size.

The amplitude of the clutter and the target-to-clutter ratio with which a radar has to deal is determined, in the first place, by a set of geometrical parameters that define the area of the patch of ground that is illuminated by the radar and, secondly, by the specific backscattering cross section of the ground itself. These parameters, the method of making the calculations, and tables of target-to-clutter ratios will be found in Appendix 3-C. Examination of the curves for clutter return over land will show that only meager and inconsistent data exist. Almost any value of σ_0 (average cross section per unit area) between −35 and −10 db could have been selected; for the purpose of calculation, a value of −25 db independent of angle and wavelength has been chosen. In justification, it can only be said that there will probably be at least as many situations in which the radar performs more poorly than the predicted result as there are in which it gives better performance. Data relative to σ_0 for sea returns are on a much more solid experimental basis and, for that reason, angular dependence has been included in the calculations; tabulated values are included in the appendix.

The success of the delay-line technique in improving the target-to-clutter ratio as it affects the radar is determined by the width of the clutter spectrum in relation to the

repetition rate; the wider the spectrum, the poorer the performance of the MTI system; within limits, increasing the repetition rate improves the performance of the system. The effect on the width of the spectrum of the inherent motion of the sea or the land, of the scanning motion of the antenna, and of the motion over the terrain of the platform on which the radar is mounted are all discussed in Appendix 3-C.

The effect of the inherent motion of the land on the spectrum width is always much less than that of rough sea; inherent motion may limit the performance of the MTI system when the antenna is looking over a narrow range of angles close to the ground track of the aircraft. At wider angles, platform motion is usually the major contributor. Since the width of the spectrum due to inherent motion is inversely proportional to wavelength, sea motion gives rise at X-band to large spectral widths, which makes MTI almost useless. This fact forces the choice of wavelength toward the larger value. The width of the spectrum due to platform motion varies inversely with horizontal antenna aperture, directly with the aircraft velocity, and directly with the sine of the angle made between the normal to the antenna and the ground track of the aircraft. Because of the high velocity of the modern interceptor, it is platform motion that causes MTI performance to deteriorate rapidly when the antenna is pointed only a few degrees off the ground track. This effect is independent of frequency; it can be minimized only by slowing the aircraft or by increasing the size of the antenna.

These statements can be summarized as follows:

> Platform motion places a limit on the angle off the ground track at which the MTI system can perform satisfactorily.
>
> The only practical way in which the angle can be widened, at any frequency, is by increasing the horizontal antenna aperture.
>
> Inside this angle, the inherent motion of the terrain and the scanning clutter determine the performance of the MTI system; the performance can be improved only by choosing a lower carrier frequency, that is, a longer wavelength.

The performance of a series of radars all having the same pulselength (one μsec), the same peak power (one Mw), and the same repetition rate (1000 pps) were calculated; the details of the calculation will be found in Appendix 3-C. These calculations are summarized in Figs. 3-1, 3-2, 3-3 and 3-4 (reproduced from Appendix 3-C).

Two distances, 15 and 30 nautical miles, are considered for two altitudes, roughly 2000 and 5000 feet. In each figure – plotted against antenna aperture as ordinate and wavelength as abcissa – are contours of unity target-to-clutter ratio, each marked by an angle. For angles (made between the normal to the antenna and the ground track)

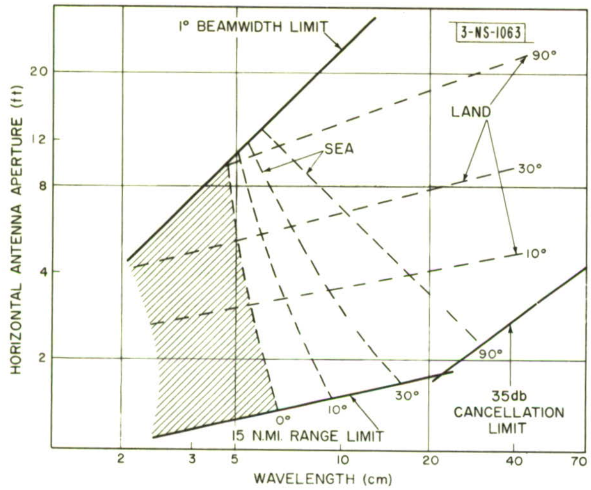

Fig.3-1. AI radar capability with MTI over land and rough sea. Altitude: 2100 feet; range: 15 nautical miles; speed: 500 knots.

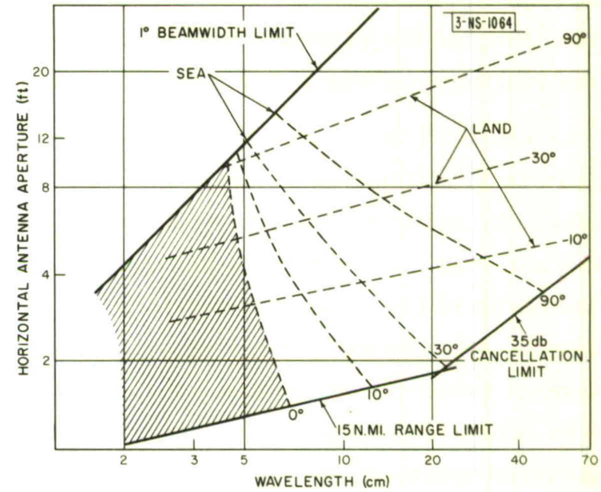

Fig.3-2. AI radar capability with MTI over land and rough sea. Altitude: 5000 feet; range: 15 nautical miles; speed: 500 knots.

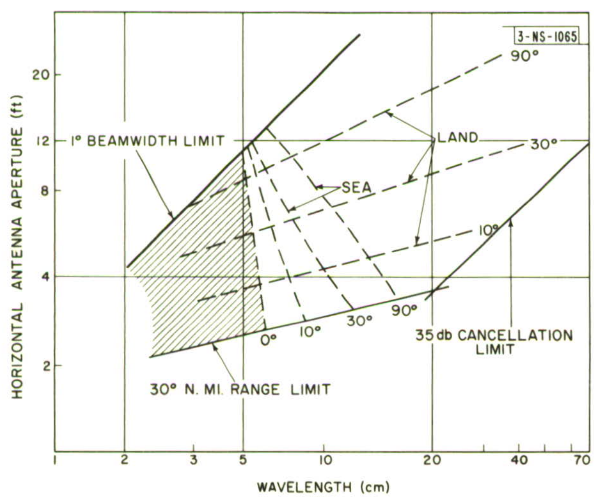

Fig.3-3. AI radar performance with MTI over land and rough sea. Altitude: 2500 feet; range: 30 nautical miles; speed: 500 knots.

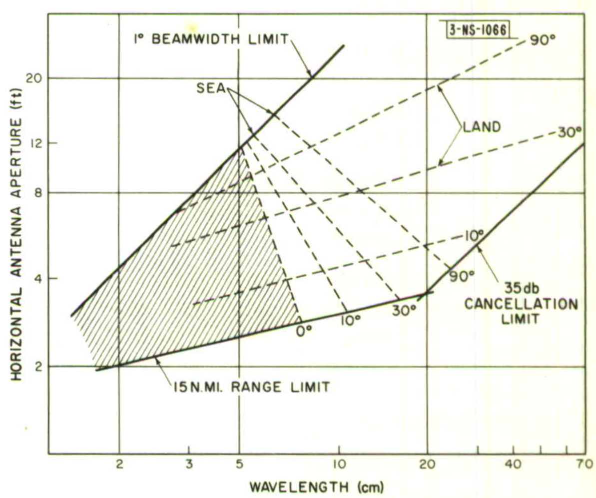

Fig.3-4. AI radar capability with MTI over land and rough sea. Altitude: 5500 feet; range: 30 nautical miles; speed: 500 knots.

less than those shown on the contour, the computed target-to-clutter ratio will be unity or greater after the incident target-to-clutter ratio has been improved by the action of the delay-line system. The diagram has been limited across the top by a contour above which the beam of the radar becomes too narrow; across the bottom it is limited by two lines, one of which is a contour below which the free space range is less than 15 (or 30) miles, and the other a contour below which the cancellation of the MTI systems exceeds the practical limit of 35 db. In all cases, double-delay MTI has been assumed.

Certain conclusions can be drawn and recommendations can be made from information contained in these diagrams, but before doing so it is important to recall that these results are for specific radars, flown at low altitude against small targets over difficult terrain. All these conclusions are based on the performance of radars equipped with double-delay MTI; without MTI, the conclusions would be greatly affected by the fact that wide beams resulting from low frequencies would increase the altitude below which the radar is incapacitated by ground clutter. Subject to these restrictions, the diagrams indicate that, over land, there is no choice of wavelength that will permit a radar equipped with a 2-foot antenna to see targets other than those along the ground track or close to it; it is interesting that, with fixed antenna size, the situation improves slightly toward the shorter wavelengths but is always unsatisfactory. Over sea, the performance is better at longer wavelengths but is still unsatisfactory. At a wavelength of 3 cm, over land, a 4-foot antenna leads to fairly satisfactory performance but this combination is useless over the sea.

Figures 3-1, 3-2, 3-3 and 3-4 present the results of calculations on radars all of which operate at a recurrence frequency of 1000 pps. The recurrence frequency has a pronounced effect on the performance of the MTI system; Fig. 3C-2 in Appendix 3-C shows that, in many cases, doubling the recurrence frequency leads to a 10-db improvement in the cancellation ratio. The repetition rate, however, cannot be increased indefinitely; it is limited by the maximum unambiguous range that is required, and limited also by the presence of second-time-around echoes which confuse the display and may obscure targets. A repetition rate of 3000 pps will permit operation out to 25 miles; before making conclusions concerning the parameters of radars for interceptors, it is necessary to explore the effect on the MTI system of repetition rates up to this limit.

It is planned that the new generation of interceptors will be equipped with an antenna 40 inches in diameter. Accordingly, calculations were carried out for an antenna of this

size and curves drawn showing how the look angle* varies with wavelength. The values of σ_0 for these calculations were taken from Table 3C-I. Three pulse repetition rates (1000, 2000 and 3000 pps) were used, and four cases were calculated: altitudes of 2100 and 5100 feet, and ranges of 15 and 30 miles. In all cases, the radars were assumed to be equipped with a double-delay MTI system.

The results of these calculations are summarized by Figs. 3-5 and 3-6 both of which refer to the performance of a 1-Mw radar emitting a 1-μsec pulse and using a 40-inch antenna, carried by an interceptor flying at 500 knots over rough sea. On these diagrams, the ordinates are the look angle in degrees and the abscissae are wavelength

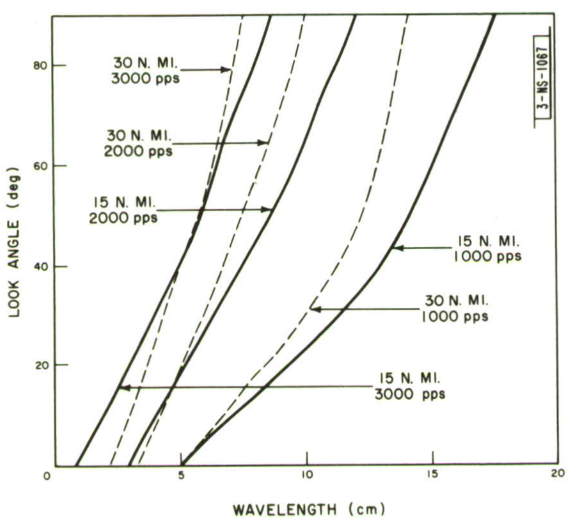

Fig.3-5. Summary of calculations on 40-inch (horizontal aperture) antenna. Rough sea; altitude: 2100 feet; speed: 500 knots.

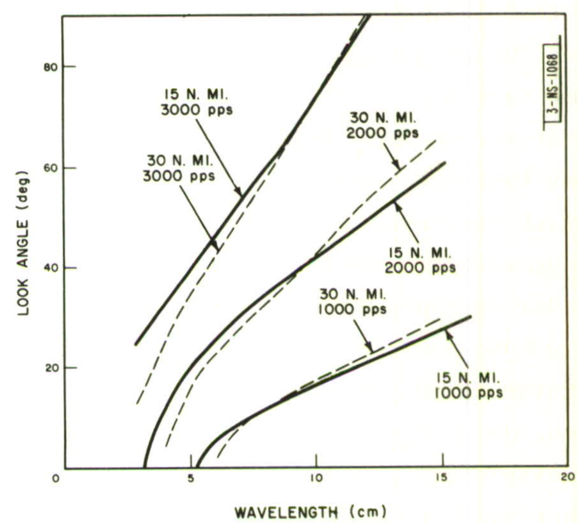

Fig.3-6. Summary of calculations on 40-inch (horizontal aperture) antenna. Rough sea; altitude: 5100 feet; speed: 500 knots.

in centimeters. It is apparent that, even at a recurrence frequency of 3000 pps, satisfactory performance cannot be obtained over rough sea from a radar operating at X-band with a 40-inch antenna. On the other hand, at a wavelength of 10 cm and a recurrence frequency of 2000 pps, the performance is quite satisfactory.

Although an X-band radar with a 40-inch antenna can be made to give marginal performance over land at low altitude, it must be concluded that, if the same radar is expected to offer satisfactory operation at low altitude over both rough sea and land, then X-band must be abandoned as a choice of wavelength for interceptor-pulsed radars even when these are equipped with an MTI system.

---

*The angle off the ground track at which the clutter spectrum becomes so wide that the target-to-clutter ratio becomes unity.

Check

Clutter interference could be greatly reduced if methods of eliminating platform clutter were introduced. Arrangements have been studied whereby two antennas cooperate to transmit and receive successive pulses as if they originated from and returned to identical points in space. The required mechanical displacement of the antennas is not large, but there are real difficulties in finding space for two antennas and the accompanying mechanical equipment in a fuselage that at present is too small for one antenna. It is recommended that research be initiated on this two-antenna technique as applied to AI radar.

CLUTTER REJECTION BY OTHER TYPES OF RADARS

Known to be under way on several types of radars are development projects to make signals visible in the midst of clutter by methods other than delay-line MTI. These are FM-continuous wave radar, and pulse-Doppler radars.

FM-Continuous Wave Radar

The Raytheon Manufacturing Company has under development the APG-43 radar which is designed to operate on X-band as a CW radar in the tracking mode and as an FM radar after lock-on. Within certain restrictions which will be discussed later, this radar offers early, tolerable AI performance at the lowest altitudes. A series of flight tests has indicated that, when flown against an F3D (4-m^2) target at 500 feet over land, the lock-on range of the set is 11 miles for an 80 per cent cumulative probability of lock-on. A detailed description of this radar will be found in Appendix 3-D.

This detection range of the APG-43 at low altitude is obtained only when the radar moves toward its target at a velocity greater than that at which the radar moves over the ground; in other words, the interceptor must be flown somewhere in the forward hemisphere of the bomber and in such a direction that the closing speed is greater than the interceptor's own speed. By this means, the Doppler return from the bomber is at a frequency higher than the Doppler returns from the ground, with the result that the target can be discriminated from clutter even in the midst of extreme clutter. In the absence of clutter, an attack can be made from any direction.

for $\epsilon = 1.25$ $\varphi < 114°$

During the detection phase, this radar operates on velocity only; range information is not available. During the lock-on phase, range information is available to an accuracy of about 10 per cent. Azimuth and elevation information can be supplied during both phases. At the present time, all information is supplied to the operator by means of meters; an azimuth-against-elevation display could be provided, but it is unlikely that a standard azimuth-range display would be possible with this equipment.

Although detection at low altitude takes place only in the forward hemisphere, there is evidence that, after lock-on, the target may be tracked from the forward into the rear hemisphere. This type of tracking has been successfully demonstrated at an altitude of 500 feet using the Sparrow III radar which has less angular discrimination and hence has to contend with more clutter than the APG-43.

In this equipment, the transmitted signal is isolated from the receiver, not by a time interval, but rather by the physical separation of the transmitting and receiving antennas. It must be pointed out that this reacts on the design of the aircraft, for it is essential that at least one and perhaps two antennas be carried in pods under the wings, as well as a receiving antenna in the nose. The isolation of the transmitting and receiving antennas determines the range of this radar; noise and microphonics carried by the transmitted signal as leakage into the receiver act to raise the effective noise figure of the receiver and, thus, to limit the range of the radar. Buck-off systems to neutralize such leakage are under development, but have not yet been tried in the radar; the ultimate range of this radar, in consequence, is still an open question. There are, therefore, two problems that arise from the nature of this radar, and these are not wholly reconcilable: the range of the radar depends on the physical isolation of the transmitting and receiving antennas, but this requirement in turn imposes an aerodynamic problem through the necessity of carrying wing pods on a swept-wing interceptor.

The APG-43 radar is the only equipment likely to make possible interceptions at low altitude within the next two or three years. In order to make use of its capabilities, new tactics which involve a forward hemisphere attack and which substitute a knowledge of closing velocity for range must be developed. Further, because this radar is unlikely to equal the performance of pulse radars at high altitudes, interceptors will
not if the S.L. perf. is enough at alt.
be forced to carry two radars; or else the equipment of interceptors must be diversified so that some are equipped for optimum high-altitude performance and others for optimum performance at low altitude with a compromise capacity at high altitude.

It is recommended that every effort be made to expedite the development of this radar and of tactics to make the fullest use of its capabilities. One, or at the most two, aircraft types and the weapons to be used with them should be designated for this purpose at once so that the interceptor weapons system design can proceed simultaneously with the work on the radar. Further, tactical tests should proceed in parallel with the prototype design. Only in this way can it be expected that this radar will be available for operational use within the next two years.

The Ryan Aircraft Company, which has had some years of experience with CW radar, is engaged at present in the development of a CW seeker for the Bomarc missile. Examination of the system has indicated that it cannot be transformed directly into an AI radar, but it is evident that the experience of this company could be useful if a large-scale development program of CW radar is planned.

Pulse-Doppler Radars

It is probable that pulse-Doppler radar possesses characteristics that will make it eventually the most satisfactory choice for use in interceptors at both low and high altitude; much applied research and development remains to be done before this prediction can be tested by actual flight trials. Nevertheless, it is recommended that high-priority programs, aimed at the early exploitation of the pulse-Doppler principle, be instituted in several laboratories.

Several forms of pulse-Doppler radar have been examined, and probably other variants exist or can be devised. One form derives from the Bomarc target seeker, the details of the other have been worked out by T. R. Silverberg of the Lamp Light Radar Group; both are described in some detail in Appendix 3-E. Except in the important matter of the treatment of the Doppler information contained in the returned pulse, there are few differences between an ordinary radar equipped with MTI and a pulse-Doppler radar: both emit short pulses which are received, after reflection, by a common antenna and passed to a superheterodyne receiver through a TR switch. The unique feature of the pulse-Doppler radar is its ability to sort the returned signals from moving objects by the Doppler frequencies associated with them, whether this occurs before or after range gating.

The ground or sea that moves under the radar in an aircraft returns to it an echo that exhibits a Doppler-frequency spectrum whose upper limit is appropriate to the aircraft's own ground speed; above this limit in a perfectly linear receiver, there are no Doppler frequencies associated with clutter. Echoes from a second aircraft bring to the radar Doppler frequencies proportional to the closing velocity of the two aircraft; provided this closing speed is greater than the ground speed, the Doppler frequency from the second aircraft is at some frequency higher than the clutter limit. Consequently, interceptors equipped with pulse-Doppler radars and flying at low altitudes – like those equipped with CW radars (and in fact for the same reasons) – must attack in the forward hemisphere of a bomber. At higher altitudes, when the clutter disappears or is not so extreme, the forward-hemisphere requirement is relaxed and

an attack can be made from any direction. It may be added, as a speculation, that there is possibility of constructing circuits that at all altitudes would permit this radar to detect and track at closing velocities lower than the interceptor's own speed.

Earlier, it was suggested that the high-altitude clutter-free performance of the CW radar would prove inferior to that of the conventional radar; this suggestion was advanced because it is thought that at high power the separation between the transmitting and receiving antennas can never provide sufficient isolation to prevent transmitter noise from limiting the receiver performance. This criticism does not apply to the pulse-Doppler radar for, in common with the conventional radar, time separation instead of space separation is used to obtain isolation. There seems to be no reason why the high-altitude range of a pulse-Doppler radar should not approach that of a conventional radar, if a sufficient number of filters is employed.

The pulse-Doppler radar does not give range information in the simple unambiguous manner typical of the conventional radar; this arises from the fact that echoes are sorted by velocity and not by range. The sensitivity of the pulse-Doppler radar depends on the use of filters of narrow bandwidth to discriminate between coherent Doppler signals and noise. The repetition frequency is so high that for any but the closest targets a number of pulses is emitted during the time taken by any one to complete a return journey; in this way, more or less ambiguity enters into the range information. Several ways of resolving this ambiguity are described in Appendix 3-E; but, in fact, no small amount of applied research will be needed before range information can be supplied with a precision and through a display that competes with the conventional radar.

RECOMMENDATIONS

In view of the serious consequences that could result from the inadequacy of pulse radars at low altitude, the research and development programs that are recommended below should be regarded as urgent. These programs should be initiated with all possible speed, and sufficient money and effort should be expended to halve the time required for normal accomplishment. In the most real sense, the effort expended in closing the low-altitude gap is a measure of the sincerity with which the Russian threat is viewed.

The APG-43 continuous-wave, X-band radar, if development is sufficiently encouraged, can be available within two years; it is regarded as the only early, albeit temporary, solution to the low-altitude problem. It is recommended that every effort be made to

have this radar operational in the shortest possible time. It is recommended also that the strengths and weaknesses of this radar be studied operationally, and that tactics be devised to exploit its abilities. It should be noted that in some cases this radar can be used only in forward-hemisphere attacks.

For tolerable low-altitude performance over both sea and land, it is mandatory that interceptor aircraft be equipped with an antenna having an horizontal aperture greater than 40 inches. It is recommended that an immediate study program be started to discover the manner in which interceptor aircraft can be modified or built to carry these antennas.

It is recommended that a program, with the highest priority, be initiated for the development of an S-band radar with a large antenna to be carried in interceptor aircraft. The performance would improve roughly in proportion to the horizontal antenna aperture as the size of the antenna was increased. As an illustration, this radar should emit 1-μsec pulses of 1-Mw peak power at an average recurrence frequency of 1000 to 2000 pps; it is essential that the radar be equipped with double-delay MTI and that in it provision be made, either by the use of several recurrence frequencies or by some other means, to remove the blind speeds resulting from the use of conventional MTI.

It is probable that pulse-Doppler radar can be developed to give performance at high altitudes comparable to pulse radar and at low altitudes comparable to CW radar. It is recommended that high-priority programs of applied research and development be initiated at once on this type of equipment. The major characteristics of the radar might be as follows: a 25-kw, 2-μsec pulse at S-band would be emitted from a 40-inch or larger antenna. A recurrence frequency of about 25 kcps in this case leads to a free-space detection range of 30 miles. The design of the equipment and the choice of recurrence frequency must be such that, by proper manipulation, unambiguous range information can be extracted from the range-gate and filter system.

An attempt has been made to survey the performance of AI pulse radars as a function of antenna size and carrier frequency, it being assumed that the radars were equipped with a double-delay MTI system. It has been concluded that there is no wavelength at which such radars equipped with a 2-foot antenna will give satisfactory performance over both rough land and rough sea at low altitude. Even with an antenna greater than 40 inches in diameter, an X-band radar can be made to give only tolerable low-altitude performance over rough land; but it would be useless over rough sea. It is therefore recommended that conventional X-band AI radars be replaced with other types as soon as these become available.

The recommendation in the preceding paragraph could be modified if displaced-phase-center antennas were introduced and if they were successful in eliminating platform-motion clutter. Research should be encouraged for the development of antennas of this type, in the hope that radar design may be revised during the next decade. Among other recommendations concerning antennas, it is suggested that effort be directed toward the study of lens antennas for use in interceptors.

Predictions concerning the performance of airborne radars are based on a knowledge of the fundamental properties of clutter in those situations where the target must compete with clutter returns; an accurate knowledge of these fundamental properties could save time and money which must now be expended on cut-and-try experiments. Information on the average cross section per unit area and on the widths of clutter spectra, particularly over land, is very meager. It is recommended that steps be taken to stimulate interest in the study of clutter at wavelengths other than X-band.

REFERENCES

1. W.H. MacWilliams, The Navy Intercept Project at Bell Telephone Laboratories, Case 26656-1 (3 March 1954).
2. Studies in progress by W.L. Baumberger, Bell Telephone Laboratories.
3. "AI Radar – Present and Future," R.S. Sargent, Head, Radar Section, Bureau of Aeronautics, presented at Lamp Light briefing, Norfolk, Virginia.

CHAPTER 3 RECOMMENDATIONS

1. *As the only available interim solution to the problem of inadequate low-altitude performance of AI radar, we recommend a maximum effort to have the APG-43 continuous-wave X-band radar operational in the shortest possible time. Operational studies with this radar are required to determine optimum tactics.*

2. *We recommend the development, with high priority, of a high-power, large-antenna, S-band AI radar. We visualize a peak power of one megawatt, a recurrence frequency of 1000 to 2000 cps, an antenna aperture larger than 40 inches, and double-delay MTI with provision for eliminating blind speeds. An immediate study program is suggested toward modification or design of interceptor aircraft capable of carrying antennas of the necessary size.*

3. *We recommend that research and development programs be established on pulse-Doppler radar design. Adequate high- and low-altitude performance may be obtainable with an S-band radar emitting 25-kw 2-μsec pulses from a 4-foot antenna at a recurrence frequency of 25,000 cps.*

4. *As a possible means of improving the inadequate low-altitude performance of conventional X-band AI radars, we recommend research on displaced-phase-center antennas.*

5. *To reduce the sidelobe levels of AI radar antenna installations, we recommend research and development on lens and slot antennas.*

6. *We recommend studies of the fundamental properties of clutter at wavelengths other than X-band. Information is needed particularly on average cross sections per unit area, and on the widths of clutter spectra.*

APPENDICES TO CHAPTER 3

APPENDIX 3-A

PARTIAL TABLE OF AI RADARS

System	Radar	Aircraft	Weapons	Antenna Diameter (in.)	Peak Power (kw)	Pulse Length (μsec)	Recurrence Frequency (PPS)	Scan (deg) ±θ	±φ	Remarks
Existing*										
APG-35	APG-26	F2H-3	Guns	9	50		2450	30	30	Westinghouse
E1	APG-33	F94A, B F89A, B, C	Guns	12	50			60	30	Hughes, 1000 prod.
E3	APG-36	F86	2.75 FFAR		50					Hughes, 100 prod.
E4	APG-37	F86, ~~F89, F94~~	2.75 FFAR	21	250					Hughes, 3000 prod. to date
E5	APG-40	~~F86, F89~~, F94	2.75 FFAR	19	250			70	15	Hughes, 400 prod. to date
E6	APG-40	F-89								
E10	APG-51	F2H4, F3H	Guns	22	250			60	36	Hughes, 250 prod. to date
	APG-51A	F4D	Guns	22	250	0.5	910			
APG-35	APS-21	F2H3	Guns	30	250					Westinghouse, AI and search
	APS-26	F2H3	Guns	9	50		2450	60	60	Westinghouse, fire control
	APS-28	F2H3		12.5	50		2000	72	72	Westinghouse, tail warning
APQ-41	APQ-41	F2H3	Guns	24	250	0.5	500,2000	60	60	Westinghouse
Aero 13	APQ-50	F10F-1, F3H-1 F4D-2, F2Y-1	Guns 2.75 FFAR	24	200		550,1200	60	60	Westinghouse
E5	MG-2	CF-100		19	250					Hughes
E9	MG-3	F89D	2.75 FFAR GAR 1, 1D	24	250					Hughes, first prod. May 1955
Planned*										
LRIX**										
	APG-43	Unknown	Sparrow III TX RX	 24 16	60 w (av)			60	60	Raytheon
MA1 (MX1179)		F102B	GAR-1A GAR-1C	24	250	0.5	2000 4000			Hughes, full prod. 1958

*See existing and planned AI radars to operate at X-band

**Characteristics not yet fixed

APPENDIX 3-B

LOW-ALTITUDE LIMITATIONS IN AI RADAR

The detection ranges of AI radar sets appear to be unaffected by altitude above about 5000 feet; below this value, they deteriorate rapidly, so that at 500 feet they have diminished to about one mile. The cause of this is the occurrence of echoes from the ground or sea which obscure the target signal. The elementary computations below serve to bring out the important features of this effect, and to describe the situations under which targets will be obscured by ground clutter.

True but one must be able [to] distinguish this signal

The area of ground that is competing with the target as a signal is only that portion which is at the same range as the target (within one pulselength). Referring to Fig. 3B-1, we see that for low altitudes and long ranges this area consists of an annulus of radius R (the range of the target) and width $c\tau/2$ where c is the velocity of light and τ the pulselength. The total area competing is $2\pi Rc\tau/2$. In general, this area is not evenly illuminated (nor is the return from various points equally effective in the receiver) because of the antenna pattern. The shaded area directly under the target represents the main beam hitting the ground near the range R; the two other shaded areas represent the intersection of the cones of the first sidelobes with the range circle; there will be similar fluctuations in illumination over the entire circle.

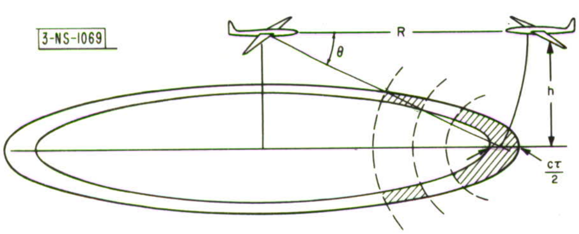

Fig. 3B-1. Geometry of clutter return.

Consider the case where the main beam does not touch the ground under the target but the first sidelobe does. The area that it illuminates will be $c\tau/2$ long, and will have a width roughly approximated by the radius of the cone at this range. The first sidelobe angle is typically about 6°; at 10 miles the patch is then one mile or 1800 meters wide, and for a 2-μsec pulse will be 300 meters long. If the reflectivity of the ground is −25 db (see Appendix 3-C), the effective reflecting area is 1800 square meters. A typical small target is 2 m^2, leaving a ratio of 900, or 30 db, to be accounted for by the antenna pattern. To be free of clutter from this cause, it should suffice, then, to provide a 15-db ratio between first sidelobe and main-beam intensities. Since antennas are usually designed with 20- to 25-db sidelobes, it can be concluded that there need be no difficulty from the first sidelobe, provided this level is maintained in the aircraft installation.

Less specific information is available relative to the remainder of the sidelobe energy. If 30 per cent of the transmitted power goes into sidelobes beyond the first, the average

intensity over the sphere cannot exceed —40 db relative to the main beam. The entire area of the annulus at 10 miles is 3.5×10^7 m^2, or an effective area 47 db more than a 2-m^2 target. The 80 db attenuation provided by the two-way antenna pattern is more than ample to take care of this. Even if the concept of a smooth illumination 40 db down be exchanged for that of an uneven pattern having patches with 50 times the average intensity over 1/50 the area, the target remains clutter-free.

When the main beam illuminates the ground under the target, the area of the patch at 10 miles is about 3.5×10^5 m^2, or an effective reflecting area 27 db more than the target. In this case there is no help from the antenna pattern; both target and ground are equally illuminated, and the target is hopelessly obscured by the clutter.

It is evident that, under the circumstances described above, detection can take place only when the main beam is off the ground. This statement bears a little amplification; it has frequently been subject to erroneous interpretation.

The AVC or logarithmic response of the AI radar receiver suffices to prevent one scan from being obscured by clutter from a previous scan; in order to detect the target, it is in general sufficient to make sure that at some time the beam illuminates the target much more strongly than it illuminates the ground at the same instant. This can be done by providing that the angular separation of target and ground as seen from the radar be approximately as large as or larger than the angle of the first null in the beam pattern.

Only a simple-minded theory gives this result.

The angle subtended is dependent only on the target altitude and the range; except in extreme cases, it is not affected by the altitude of the interceptor. There is thus no virtue in "flying below the target and looking up"; the point of the matter is that the width of the beam <u>at the target</u> comprises the limitation. Similarly, looking down at large angles gives a very slow improvement; at 45° only a 30 per cent decrease in the effective beamwidth is obtained.

Following this simple criterion, we find that the detection range is proportional to target altitude up to the limit set by the free space range of the radar. For a first null at 4°, the expected range at 5000 feet is 12 miles, at 2000 feet it is 5 miles, at 500 feet it is 1.2 miles. These values are quite consistent with what little data on low-altitude performance are available.

A type of clutter interference that has not yet been mentioned is the "altitude circle." line When the target is at the range corresponding to the interceptor's altitude, it must compete with a scattering area that is illuminated practically at normal incidence;

under this condition, the reflectivity may be close to unity. One may calculate readily that the vertical sidelobes should be kept down to about −40 db to avoid breaking lock-on of high-altitude targets at the range of the altitude circle. It appears that with care this can be done in practice, though the problem needs some attention.

There is no simple cure for the low-altitude problem. Narrower beams, produced by larger antennas and/or shorter wavelengths, will increase proportionately the detection range for a given altitude or, conversely, will force the enemy to fly proportionately lower to escape detection at ranges that will permit successful attack; since this altitude may be roughly 2000 feet now, a reduction to 1000 feet will not place a very severe restriction on the enemy's tactics. In view of the capability of the enemy to carry out attacks at very low altitudes, it seems urgently necessary to look to methods (MTI, CW, pulse Doppler) that may give some capability of detection at reasonable ranges for any altitude.

J.W. Coltman

APPENDIX 3-C

MTI IN PULSED AI RADAR

The low-altitude deficiencies of AI radar arise from masking of the target signal by land or sea clutter. Several modifications – for example, application of MTI, use of larger antennas, lower frequencies – offer possible solutions. In order to determine the efficacy of these, a computation has been carried out which outlines the limitations set by choice of certain parameters, points directions for improvement, and to a degree predicts the low-altitude performance of a radar as a function of several design variables.

When the target flies at a sufficiently low altitude, the main beam of the AI radar illuminates a patch of the terrain beneath the target, and the signal from the target must exceed that from the patch of terrain for detection to take place. The clutter signal depends on the range, beamwidth and pulselength, which determine the size of patch competing with the target; the signal also depends on the reflectivity of the terrain, which depends upon its nature (smooth or rough sea, forest, sand, etc.) on the angle of incidence and on the wavelength. The efficacy of MTI in separating the target from the clutter by velocity discrimination depends on the spread of frequencies encountered in the clutter. This spread is a function of the movement of the terrain (waves, trees, etc.), the scanning motion of the antenna, the velocity of the vehicle, the angle of look, the size of the antenna, and the wavelength.

There are, thus, a great many variables to introduce in making a comparison of the effectiveness of various radar designs, and it has been necessary to fix certain of the variables in order to keep the computations within reasonable bounds.

The parameters shown in Table 3C-I were used in the calculations. The computation proceeds as follows: For each range and altitude, the size of the illuminated patch beneath the target is calculated. It is assumed here that the case of interest is where the target is so low that the ground is illuminated as effectively as the target. The reflectivity of the terrain (σ_0) is then introduced, and an effective reflecting area is obtained. This is compared with the area of the target ($2m^2$), and the ratios in db are the target-to-clutter ratios given in Tables 3C-III and 3C-IV.

The value of σ_0 is an extremely important and very variable parameter. Unfortunately, experimental data are quite meager. Over land, the only available data appear to be represented by the values shown in Fig. 2B-7 of Appendix 2-B, which are taken from a Philco report[1] and from a report by General Precision Laboratories.[2] There are no available data for wavelengths other than 3 cm; but it seems plausible that the

TABLE 3C-I PARAMETERS FOR RADAR DESIGN CALCULATIONS	
Wavelengths (cm)	3.2, 10.4, 24, 70
Antenna apertures (horizontal) (ft)	2, 4, 12, 17
Ranges (mi.)	15, 30
Altitudes (ft)	2300, 5000, 7300, 15,000
Terrain	rough land, rough sea
Pulse length (μsec)	1
Repetition rate (pps)	1000
Speeds (knots)	0, 50, 100, 200, 300, 400, 500, 700
Target cross section (m^2)	2
MTI type	double delay
Terrain reflectivity	
Land	$\sigma_o = -25$ db
Sea	σ_o as per Table 3C-II

ROUGH SEA (WINDS > 15 KTS)

I would appreciate someone saying what the H-I α is?

TABLE 3C-II

σ_o AS FUNCTION OF λ, α (SEA*)

λ (cm) \ α (deg)	0.64	1.25	1.6	3.2	4.6
3.2 db	−22 db	−22 db	−22 db	−22 db	−22 db
10.4	−45	−39	−38	−34	−33
24	−62	−54	−52	−46	−43
70	−82	−70	−66	−57	−53

*Land: $\sigma_o = -25$ db for all λ, α

TABLE 3C-III

TARGET-TO-CLUTTER RATIOS (LAND) AND EFFECTIVE SPEEDS FOR DOUBLE-DELAY MTI TO GIVE 0 db*

Horizontal Antenna Aperture (ft)		2		4		12		17	
Range (n.mi.)	Wavelength (cm)	db	knots	db	knots	db	knots	db	knots
15	3.2	−26	50	−23	120	−18	x	−17	x
	10.4	−31	40	−28	90	−23	x	−22	650
	24	−35	–	−32	80	−26	330	−26	470
	70	−40	–	−35	–	−31	260	−30	380
30	3.2	−29	40	−26	100	−21	x	−20	x
	10.4	−34	30	−31	80	−27	x	−25	500
	24	−38	–	−35	70	−30	270	−29	380
	70	−43	–	−39	50	−35	200	−33	310

*σ_o was taken as −25 db at all wavelengths and angles.
Patch width = $R\lambda/a$, target $2m^2$, pulse length = 1 μsec.

variation with wavelength will not be great, and for want of better information, a constant value of −25 db was assumed. About all that can be said concerning the choice of −25 db is that there will certainly be a great deal of land area which is more favorable than that assumed, but that there will also be many cases where the situation is worse.

Over the sea, the data are somewhat less scarce, and in general are in reasonable agreement. Measurements from several sources are summarized in the General Precision Laboratories Report;[3] data at 10 and 70 cm are given by Freedman, et al. ~~in a~~ Lincoln Laboratory Report[4] and by Ross, Palmer, and Fakely (ASRE) at 10 and 55 cm. Under conditions where the sea is rough (winds in excess of 15 knots), the values of σ_o given in Table 3C-II can be taken with some assurance as typifying the situation. Over the range of parameters given, the table may be approximated by the empirical relationship

$$\sigma_o = \frac{1}{125a} \lambda^{2.1 \log_{10} a} ,$$

where a is the angle in radians (between 0.1 and 0.015) and λ the wavelength in cm.

TABLE 3C-IV

TARGET-TO-CLUTTER RATIOS (SEA) AND EFFECTIVE SPEEDS FOR DOUBLE-DELAY MTI TO GIVE 0 db

Horizontal Antenna Aperture (ft)			2		4		12		17	
Range (n.mi.)	Wavelength (cm)	Alt. (ft)	db	knots	db	knots	db	knots	db	knots
15	3.2	2100	–29	–	–26	–	–21.2	–	–19.7	–
		5100	–29	–	–26	–	–21.2	–	–19.7	–
		7300	–29		–26		–21.2		–19.7	
	10.4	2100	–17	100	–14	280	– 9.2	x	– 7.7	x
		5100	–22.3	60	–19.3	170	–14.5	x	–13.0	x
		7300	–23.3		–20		–15.5		–14	
	24	2100			– 3	x	1.8	x	3.3	x
		5100			–11	350	– 6.2	x	– 4.7	x
		7300			–14		– 9.3		– 7.7	
	70	2100			8.4	x	13.2	x	14.7	x
		5100			– 4.6	x	.2	x	1.7	x
		7300			– 8.6	420	– 3.8	x	– 2.3	x
30	3.2	2500	–32	–	–29	–	–24.2	–	–22.7	–
		5500	–32	–	–29	–	–24.2	–	–22.7	–
		15000	–32	–	–29	–	–24.2	–	–22.7	–
	10.4	2500	–14.3	120	–11.3	350	– 6.5		– 5	x
		5500	–21.3	70	–18.3	180	–13.5		–12	x
		15000	–26.3	40	–23.3	120	–18.5		–17	x
	24	2500			2	x	6.8	x	8.3	x
		5500			– 8	420	– 3.2	x	– 1.7	x
		15000			–17	200	–12.2	x	–10.7	x
	70	2500			17.4	x	22.2	x	23.7	x
		5500			1.4	x	6.2	x	7.7	x
		15000			–11.6	350	– 6.8	x	– 5.3	x

Referring to Tables 3C-III and 3C-IV, it will be seen that, over land, all the values of target-to-clutter ratio range from −17 to −43 db − i.e., the return from the clutter is 100 to 10,000 times stronger than the return from a 2-m^2 target. Over the sea, long wavelengths and large antenna apertures afford some relief, so that a 24-cm radar with a 12-foot antenna can give clutter-free detection at low altitudes.

The application of MTI to the radar can depress the clutter return relative to that of the target. This is accomplished by filtering out Doppler frequencies at and near that represented by the component of ground velocity along the direction the antenna is pointed. If the clutter return consisted of a single frequency, it could be completely cancelled; because it actually contains a spread of frequencies, the cancellation is imperfect, and the improvement attainable is more or less limited depending on the width of the clutter spectrum. The spectral width is a result of three main factors: (1) the motion of objects causing the clutter such as trees blowing in the wind, waves on the sea, etc., (2) the modulation due to scanning the beam over the reflecting objects, and (3) the differential radial velocity of objects in various portions of the beam arising from the motion of the platform carrying the antenna. Expressions for the standard deviation of the (assumed Gaussian) distributions in cycles per second are given below:

$$\begin{aligned} &\text{Sea motion:} \quad \sigma_1 = 320/\lambda \\ &\text{Land motion:} \quad \sigma_1 = 50/\lambda \end{aligned} \qquad \lambda \text{ in cm} \quad .$$

The frequencies correspond to movements in the sea of approximately 3 knots and on land of approximately 0.5 knot; the inverse dependence on λ makes the sea-clutter spectrum very wide at 3 cm regardless of radar design, making MTI relatively ineffectual at this wavelength.

$$\text{Scanning:} \quad \sigma_2 = 11.5\,(a/\lambda)\left(\frac{d\theta}{dt}\right) \quad ,$$

where a is the horizontal antenna aperture in feet, λ the wavelength in cm, and $(d\theta/dt)$ the scanning rate in radians/sec. This factor increases with narrow beams and high scan rates; in the radars examined here, the scan rate was chosen as 36° per second and the scanning clutter was a minor factor.

$$\text{Platform clutter:} \quad \sigma_3 = 1.66\,(v/a)\sin\theta \quad ,$$

where v is the speed in knots, a the antenna aperture in feet, and θ the angle off the ground track. Except for the 3-cm radar over sea, this platform clutter is the major factor to be considered. As a result, it is found in general that the application of MTI

TABLE 3C-V					
COMPONENTS OF CLUTTER SPECTRUM*					
Horizontal Antenna Aperture (ft)		2	4	12	17
Wavelength (cm)		spectrum width (cps)			
3.2	Land motion	16	16	16	16
	Sea motion	100	100	100	100
	Scanning motion	4.5	9	26	37
	Platform motion	420	210	70	50
10.4	Land motion	5	5	5	5
	Sea motion	30	30	30	30
	Scanning motion	1.3	2.7	8	11
	Platform motion	420	210	70	50
24	Land motion	2	2	2	2
	Sea motion	12	12	12	12
	Scanning motion	0.6	1.2	3.6	5
	Platform motion	420	210	70	50
70	Land motion	1	1	1	1
	Sea motion	4	4	4	4
	Scanning motion	0.2	0.4	1.2	1.6
	Platform motion	420	210	70	50

*Antenna looking at 90° to the ground track of a 500-knot interceptor.

gives good results when θ (and therefore σ_3) is small; in many cases the filter cannot suppress the wider spectrum obtained at larger angles, giving rise to a radar system that can "see" only over a restricted angle about the ground track.

Table 3C-V shows the widths of each of the types of clutter spectra for the various radars. The platform clutter is given here for a 500 knot vehicle looking broadside; at other angles the effective speed is reduced, and the computations have been carried out for a range of speeds from 0 to 700 knots. Notable in Table 3C-V are the large contributions by sea motion at 3 cm, the reduction in this factor with larger wave-lengths, and the improvement in platform clutter with increased antenna aperture.

TABLE 3C-VI									
CLUTTER-SPECTRUM WIDTHS AND DOUBLE-DELAY MTI IMPROVEMENTS (LAND)									
Repetition Rate 1000 pps									
Horizontal Antenna Aperture (ft)		2		4		10		17	
Wavelength (cm)	Knots	cps	db	cps	db	cps	db	cps	db
3.2	700	580	4	290	6				
	500	420	5	210	8				
	400	340	5	170	9				
	300	250	7	125	12				
	200	166	10	86	16				
	100	85	16	46	26				
	50	45	26	28	35				
	0	16	44	18	42				
10.4	700	580	4	290	6			71	19
	500	420	5	210	8			52	25
	400	340	5	170	9			42	28
	300	250	7	125	12			33	32
	200	166	10	84	17			23	38
	100	84	17	43	26			16	44
	50	42	28	22	39			13	47
	0	5	64	6	60			125	48
24	700			290	6	96	15	70	19
	500			210	8	70	19	50	25
	400			170	9	55	23	40	28
	300			125	12	41	28	31	34
	200			83	17	27	35	20	40
	100			42	28	14	46	11	52
	50			21	39	8	56	7	58
	0			2		4		5	
70	700			290	6	96	15	70	19
	500			210	8	70	19	50	25
	400			170	9	55	23	40	28
	300			125	12	41	28	30	34
	200			83	17	27	35	20	40
	100			42	28	14	46	10	52
	50			21	40	7	58	5.5	62
	0			1		1.5		2	

TABLE 3C-VII

CLUTTER-SPECTRUM WIDTHS AND DOUBLE-DELAY MTI IMPROVEMENTS (SEA)

Repetition Rate 1000 pps

Horizontal Antenna Aperture (ft)		2		4		12		14	
Wavelength (cm)	Knots	cps	db	cps	db	cps	db	cps	db
3.2	700	580	4	307	4				
	500	420	4	235	5.5				
	400	355	4.5	200	7.5				
	300	275	5	160	10				
	200	194	7.5	130	12.5				
	100	130	12.5	108	14.5				
	50	108	14.5	102	15				
	0	100	15	100	15				
10.4	700	580	4	290	4.5			77	18
	500	420	4	210	6			59	21.5
	400	340	3	170	9.5			51	25
	300	250	6	125	13			44	27
	200	166	10	89	16.5			38	30
	100	89	16.5	52	25			33	33
	50	52	25	37	30			32	33
	0	30	34	30	34			32	33
24	700			290	4.5	96	15.5	70	19.5
	500			210	6	70	19.5	50	25
	400			170	9.5	55	23	42	28.5
	300			125	13	43	29	32	33
	200			83	17.5	30	34	24	38
	100			43	29	18.5	42	16	44
	50			24	38	14.5	47	14	46
	0			12	49	13	48	13	48
70	700			290	4.5	96	15.5	70	19.5
	500			210	6	70	19.5	50	25
	400			170	9.5	55	23	40	29
	300			125	13	41	28.5	30	34
	200			83	17.5	27	35	20	40
	100			42	29	14.2	46	11	50
	50			22	39	8	56	6.5	59
	0			4	67	4.2	67	4.3	67

The three spectral widths for any given case are combined by the relation

$$\sigma = \sqrt{\sigma_1^2 + \sigma_2^2 + \sigma_3^2} \quad ,$$

and the total spectrum widths are given in Table 3C-VI.

The clutter rejection obtainable by application of an MTI system depends on the ratio of the spectrum width to the repetition frequency of the radar. This latter is thus an important parameter, and the higher it can be made, the more rejection can be obtained. The repetition frequency is limited by the range desired; for uniformity of comparison it has been chosen here as 1000 pps. The cancellation ratio for single-delay and double-delay systems is given by the curves of Fig. 2B-3 of Appendix 2-B. Values corresponding to the spectrum widths already calculated are also given in Table 3C-VI.

A comparison of the target-to-clutter ratios of Tables 3C-III and 3C-IV and the improvements provided by MTI from Tables 3C-VI and 3C-VII will suffice to indicate in any particular case whether MTI will provide sufficient improvement to detect the target. In general, very large improvements are required, so that the final calculations have been carried out only for double-delay MTI. In some cases MTI will not be effective at any speed, in some there will be a limiting speed less than 500 knots for which the improvement will just suffice, for others the limiting speed will exceed 500 knots. These speeds are also given in Tables 3C-III and 3C-IV. They can be translated easily into the angle ($V_{eff} = V \sin \theta$) around the ground track over which the radar can detect a target from a 500-knot aircraft; for calculated speeds in excess of 500 knots (marked "x" in the table), the radar is operable at all angles. Bars (–) in the table indicate that the radar is not operable at any angle.

The results of these calculations can be summarized by the diagrams of Figs. 3C-1, 3C-2, 3C-3 and 3C-4 (these diagrams are identical with Figs. 3-1, 3-2, 3-3 and 3-4 of the text). Before discussing these, it would be well to raise certain warnings:

> The calculations for all wavelengths are based on a very small amount of X-band data on ground return (which varies strongly with terrain).
>
> The conditions for which the calculations are valid can only be described in general terms, i.e., "rough sea," "level land," etc.
>
> Certain parameters such as pulselength and repetition rate have been fixed at more or less arbitrary values; variation of these can affect the values derived.

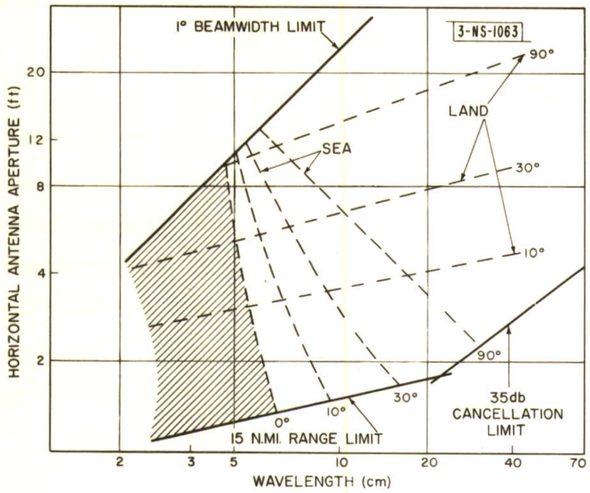

Fig.3C-1. AI radar capability with MTI over land and rough sea. Altitude: 2100 feet; range: 15 nautical miles; speed: 500 knots.

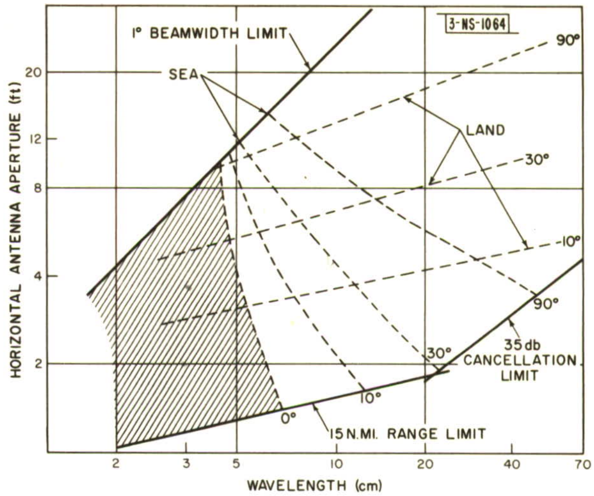

Fig.3C-2. AI radar capability with MTI over land and rough sea. Altitude: 5000 feet; range: 15 nautical miles; speed: 500 knots.

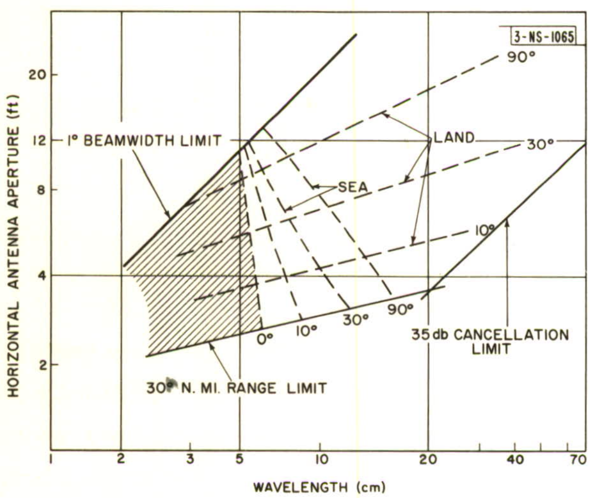

Fig.3C-3. AI radar performance with MTI over land and rough sea. Altitude: 2500 feet; range: 30 nautical miles; speed: 500 knots.

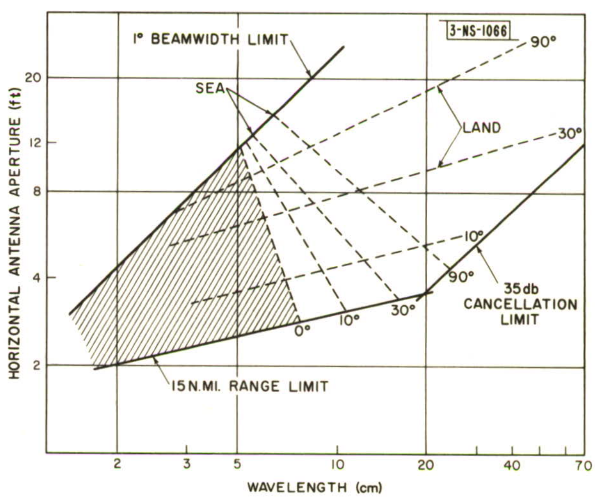

Fig.3C-4. AI radar capability with MTI over land and rough sea. Altitude: 5500 feet; range: 30 nautical miles; speed: 500 knots.

As a result, one can obtain from the curves primarily information as to trends, together with the establishment of certain limitations that do not vary rapidly with external conditions.

The diagrams display, as a function of wavelength and antenna aperture, the regions over which a radar fitted with double-delay MTI can achieve target-to-clutter ratios of unity or more. Boundaries on two sides of the diagram are formed by beamwidth limitations (1° is considered about as small as practical), by free-space range limits (calculated by assuming typically available power and noise figures at each wavelength), and by fixing at 35 db the maximum cancellation ratio that can be achieved. Within these boundaries, the efficacy of the radar is measured by specifying (for a 500-knot aircraft) the angle to which it can look without encountering excessive clutter. Contours of constant look angle are sketched in for the land and sea situations.

Examination of the diagrams shows:

> Over rough sea, 3-cm wavelengths will be completely cluttered out regardless of antenna aperture. This is a result of the wide clutter spectrum produced by motion of the sea surface.
>
> Relief from this condition is rather quickly obtained by going to longer wavelengths and moderately increased antenna size; a 10-cm radar with a 4-foot antenna will operate over look angles of approximately ±45° over the sea.
>
> Over land, larger look angles can be obtained most readily by going to larger antennas; the wavelength dependence is very slow. A 2-foot antenna gives only a very small angle; by going to 4 feet, a marginal performance (±10°) is attained; at 8 feet, the angle approximates ±45°.

While the calculations are admittedly subject to wide variations depending on the assumptions, it appears clear that the present 3-cm radars with 2-foot apertures are not going to be appreciably helped by MTI, and that larger antennas and longer wavelengths are demanded if a low-altitude capability is to be achieved by the application of MTI.

J.W. Coltman

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1. Philco Corp., "Research on Radar Terrain Characteristics," Report CD-954.
2. General Precision Laboratories, "Automatic Ground Position Indicator," Report ALL-32.
3. Ibid.
4. J. Freedman et al., "Comparative Performance of 10-cm and 70-cm Radar Over the Sea," Technical Report No. 56, Lincoln Laboratory, M.I.T. (25 August 1954).

APPENDIX 3-D

STATUS AND DESCRIPTION OF CW AI RADARS AT RAYTHEON

INTRODUCTION

A general-purpose FM/CW aircraft intercept radar, designated the AN/APG-43, is under development at the Raytheon Manufacturing Company. Originally intended to be a single-antenna radar, the specifications were changed to allow experimental two-antenna operation. Recent flight tests of this configuration have indicated appreciable low-altitude, forward-hemisphere lock-on range.

A new program aimed at the earliest attainment of a complete low-altitude weapons system is being negotiated, looking toward the construction of two "flying breadboard" radars under joint Navy-Air Force sponsorship. The first of these is to be installed in an F3D aircraft equipped for firing of Sparrow III. It is contemplated that the complete system will commence missile firing tests in April 1956 at Naval Air Missile Test Center, Pt. Mugu, California.

It must be emphasized that this program for an "all-altitude AI Doppler radar" is purely experimental. There are no plans as yet in writing for prototypes, evaluation or production. No aircraft has been designated.

THE APG-43 – PRESENT STATUS

The APG-43 radar is now installed in an F3D and has been undergoing flight tests at Bedford, Mass. The entire radar, except for the transmitting antenna, is installed in a cylindrical package in the nose of the aircraft. The present receiving antenna is a 23-inch split-paraboloid two-feed form of simultaneous lobing (monopulse) antenna. An identical radar, but having a conical-scan receiving antenna, is complete and will shortly be installed in the airplane. The transmitting antenna is a 16-inch paraboloid with on-center feed installed in a 20-inch diameter pod under the left wing.

The transmitter power radiated is 30 watts; the frequency is X-band. The receiver speedgating circuits have a predetection bandwidth of 700 cps. A block diagram is shown in Fig. 3D-1.

Tests of this system have been made head-on against an F3D target. A plot of the results of one series of runs at 4000-foot altitude is shown in Fig. 3D-2. In all the runs made to date, automatic acquisition of a simple type is employed: the antenna scans a two-bar pattern 7° by 30° azimuth (although a 7° × 60° pattern is now being

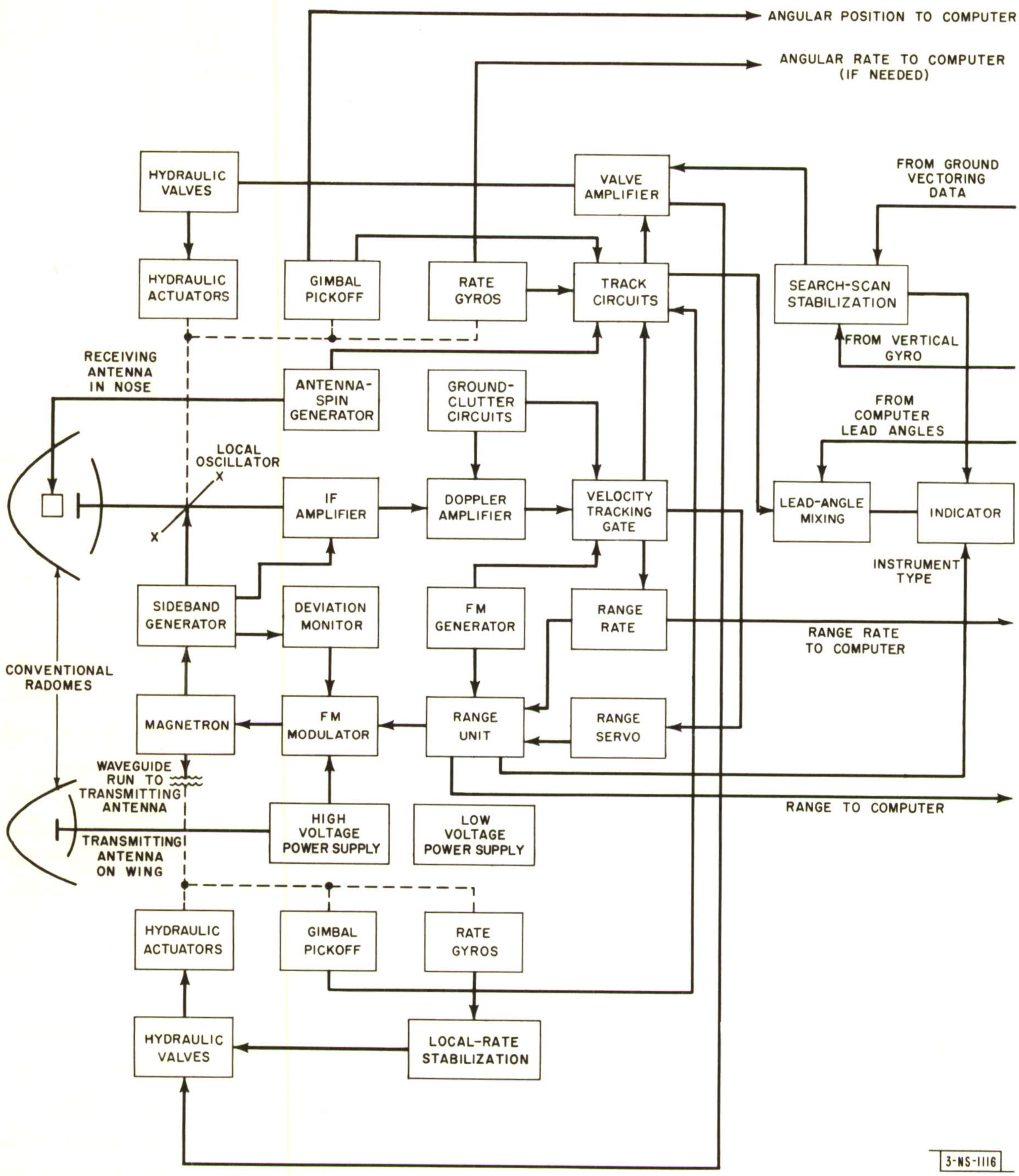

Fig.3D-1. Block diagram of AN/APG-43.

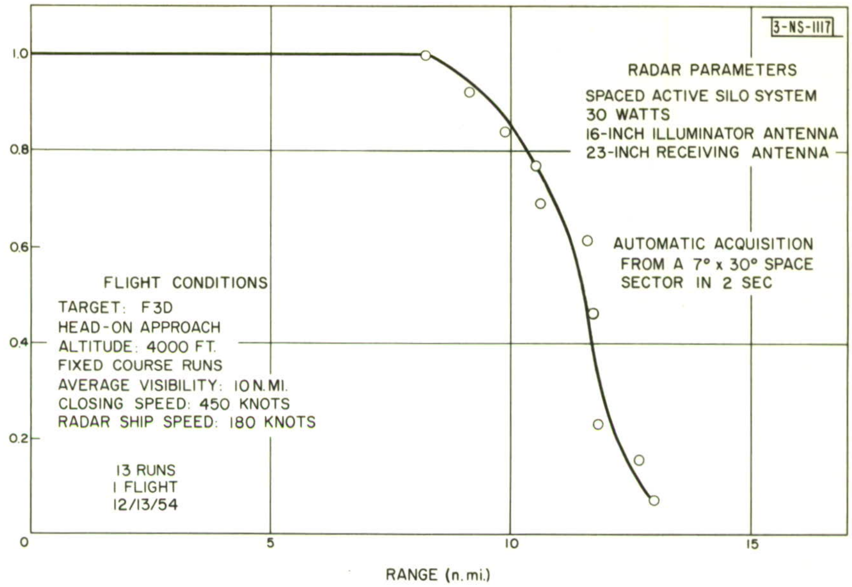

Fig.3D-2. AN/APG-43 probability of lock-on vs range.

incorporated). Simultaneously, the speedgate searches the Doppler spectrum from the aircraft's own speed upward to several hundred knots. The lock-on threshold is set for a low false-alarm rate. Whenever a target is detected in the speedgate, the hydraulic gimbals are momentarily stopped. The speedgate then evaluates the signal for coherence. If it is found to be coherent, track continues. Otherwise search is immediately resumed.

The pilot's only indication is a lock-on light and a cross-pointer instrument which gives him the course to fly. He has a control stick to set the sector being searched within the gimbal frame of ±60° in each plane.

Radar Requirements

THE ALL-ALTITUDE AI DOPPLER RADAR – CURRENT PLANS

The prime requirement for the all-altitude AI Doppler radar program is to design and build a spaced-active experimental Doppler radar system for all-weather missile launching, and to prove the basic concept of the system in the air. This AI radar is intended to work satisfactorily at all altitudes from 50,000 feet down to less than 500 feet over both land and water. Low-altitude operation, in particular, will be emphasized. Appropriate missile integration is to be provided. Operation is to be as simple as possible, and the design objective is for the system to

be operated by the pilot alone. With this end in view, automatic lock-on and tracking will be needed, and, because both high-speed closing targets and tail chases will be encountered, the radar will be capable of operation with relative speeds at least over the range of 50 to 2000 knots.

Missile Applications

The proposed radar will be designed in such a way as to be fully effective in launching missiles of the semiactive CW, active pulse, or the infrared types. Whereas these missiles are capable of working satisfactorily at low altitude, the means of positioning an aircraft to take advantage of these characteristics have not yet been developed. A spaced-active CW radar system logically offers the greatest immediate promise towards eliminating this deficiency.

The effectiveness of the radar design depends also upon adequate integration with the missiles. It is proposed in this program that integration should be provided specifically for Sparrow III. The requirements for integration with missiles such as Sparrow II, Sidewinder and the infrared Falcon will be investigated. At the present time, there appears to be no good reason why the radar should not serve these missiles in addition to Sparrow III and such an objective for the radar design is, therefore, extremely desirable.

So far as integration with Sparrow III is concerned, provision would be made for ranging modulation and for coding. The requisite outputs for range data, for velocity indication, and for gimbal position would be provided. Missile klystron-tuning arrangements will also be taken into account.

Radar Performance

With the increase in speeds of modern aircraft, the utmost in AI radar performance in range is demanded. The recent work on the APG-43 has shown that, with 30 watts of output power and using automatic lock-on, over restricted search angles, good radar performance can be obtained down to altitudes below 500 feet.

Potentially this already good performance can be improved by increasing transmitter power, by receiver refinement, and by using cavity stabilization in the transmitter. It is intended that the proposed program take full advantage of the possibilities offered. The objective will be to attain a detection and automatic lock-on range of more than 12 miles on an F9F type target with high probability and at all altitudes.

Tracking accuracy will be adequate to retain lock, to illuminate the target for CW missile guidance, and to position the aircraft for launch of appropriate missiles. The radar will be capable of providing range information after lock-on. For CW missile use, the requirement presently is for ranging to be performed between 500 yards minimum and 15,000 yards maximum to an accuracy of ±5%. (This requirement may eventually be modified slightly as operating experience is gained.)

At present it is believed that a gimbal angle of ±50° in both azimuth and elevation would be adequate for launching missiles. This is to say that the gimbals will be capable of tracking anywhere over these angles but not necessarily that the search sector could cover the full angle in azimuth under all conditions. The exact search angle to be used would be chosen as the program advances. Present thinking suggests that it might well be a two-bar scan of ±30° in azimuth by 11° in elevation. (A three-bar scan, without spinning, could also cover the same area.) At a range of about 12 miles, an area of space about 12 miles wide by 13,500 feet high would be searched. Evaluation of the tactical employment of the radar is very desirable, and the adequacy of the search sector could be determined during this work.

Since stabilization of the search sector in space is a requirement, it is also intended that the stabilized sector could be positioned anywhere within the full gimbal angles. Stabilization would be in roll and pitch. Stabilization in track will be included in the radar and full advantage of this will be taken to enable the radar to retain lock-on and tracking through zero Doppler conditions under all reasonable expected tactical situations.

It is anticipated that the radar will operate satisfactorily on opening targets with less than 50 knots differential speed, either at reduced sensitivity or for limited periods of time (as in the zero Doppler condition.) The upper limit to which the radar will be designed to work is a closing velocity of 2000 knots. This corresponds to approximately Mach 3.5 above 35,000 feet and to Mach 3.0 at sea level.

Automatic Acquisition

Recent work on the automatic-acquisition problem has shown that short time-on-target need not necessarily result in serious reduction of system sensitivity. The existing rate of Doppler sweep can be increased by over 3 to 1, and this improvement can be reflected directly in reducing frame time. This work will continue; the further useful results to be expected will be incorporated directly into the design of the proposed

radar and will in large measure determine the space-scan parameters. The automatic-acquisition work done to date on the APG-43 has only been with single-velocity tracking gates and has as yet drawn no benefit from the recent laboratory work. Multiple sweeping gates have not yet been tried in the air, nor has an increased rate of velocity scan been employed.

It is proposed that the experimental radar be constructed in the first instance with a variable azimuth scan (and perhaps also a variable elevation scan), and arranged to have an adjustable frame time. It is hoped by these means to optimize both electronically and tactically the space search and automatic lock-on scan sector.

Antenna System

It is proposed that two antennas be fitted. The receiving antenna will be in the nose of the aircraft and will use a 23-inch (approximately) conically scanning receiving antenna. The transmitting antenna will be approximately 16 inches in diameter with an on-center beam. The transmitting antenna gimbals will be hydraulically operated. Stabilization in pitch and roll will be included for the search function, and rate stabilization will be employed for the tracking function.

Ranging

The requirements for ranging are considerably less than those demanded by a fire-control system operating with guns and rockets. Nevertheless, certain demands are made which have to be fulfilled for missile launch and flight. Constant-deviation frequency modulation is proposed because the dynamic ranging ratio of from 500 to 15,000 yards should permit simple use of this system. Range accuracy of ±5 per cent is the objective. Low deviation is desirable because of the effects of ground return. Range data can be provided from the radar as a DC voltage or as a shaft position.

Indicator and Controls

Since it is intended to make the operation of this radar a pilot's responsibility, the controls and indicating equipment would be kept simple and to a minimum. Also, since the time will be short due to higher aircraft speeds, a multitude of operations will have to be carried on in a very short period of time. For this reason, it is desirable to make many of the operations automatic and independent of the pilot. During the early part of the program at least, very simple indicating equipment will be used with this system. The first indicator may be of the cross-pointer type giving the operator just enough data to fly his aircraft toward the target. Range and speed can be conveniently

displayed on meters. As the program progresses, consideration will be given to other types of indicating equipment with a view towards displaying to the pilot in a convenient form more of the data that are available from the radar. This will enable the pilot to have a better appreciation of the over-all tactical situation and will make the radar a more useful tool. The control equipment will be integrated with the missile launching controls to keep armament operation simple.

W.R. Hutchins

APPENDIX 3-E
POSSIBLE PULSE-DOPPLER PARAMETERS

INTRODUCTION

In the search for a reliable means of aircraft interception by radar at all altitudes, preferably using only one antenna, it has been concluded that a high-repetition rate, coherent, pulse-Doppler radar shows the most promise. A radar of this general type has been under development at Boeing Airplane Co. for several years for eventual use as the Bomarc target seeker. Another radar, similar in principle though not in detail to the Boeing radar, has been considered at Project Lamp Light. Both are described below.

GENERAL

Pulse-Doppler radars provide a high degree of velocity discrimination, as do CW radars; velocity discrimination is believed to be the only practicable way of overcoming the AI clutter problem. The advantages of pulse-Doppler over CW radars are:

> Time separation prevents transmitter energy from feeding into the receiver; the ultimate range of the pulse-Doppler system is not limited by feedthrough as it is in the CW system.
>
> Range discrimination by range gating reduces the clutter with which the signal has to compete, and this leads to more sensitivity in clutter than is obtained with the CW system.
>
> More accurate range tracking is possible in the pulse-Doppler case – probably as accurate as is now achieved in the standard pulse radars.

Both the pulse-Doppler and CW systems can be made fully automatic in the presence of clutter exceeding the desired signal by many db (well over 30 db at present), for forward-hemisphere attacks and targets at all altitudes. At high altitudes, attack from any angle should be possible; after some development work, reasonable effectiveness from any angle at low altitude is a possibility but should not be depended upon at this time.

Both CW and pulse-Doppler radars, with narrow predetection bandwidths, are more difficult to jam than are conventional radars. As to chaff, these radars are practically immune to all normal varieties.

ILLUSTRATIVE SYSTEM

The following system is presented for concreteness in this discussion. As concerns number and width of range gates and filters, or even the basic parameters, it may not be the exact system that one should use for AI but it seems to present a reasonable starting point for AI design; its performance can be predicted and the effects of changing parameters can be seen.

The system is so arranged that it will acquire automatically and subsequently track targets moving radially with respect to own aircraft at speeds between own speed (here taken as 600 knots) and 1250 knots; in other words, it will operate against all subsonic vehicles at low altitudes for forward-hemisphere attacks. Changes in parameters can be made to extend operation to supersonic speeds.

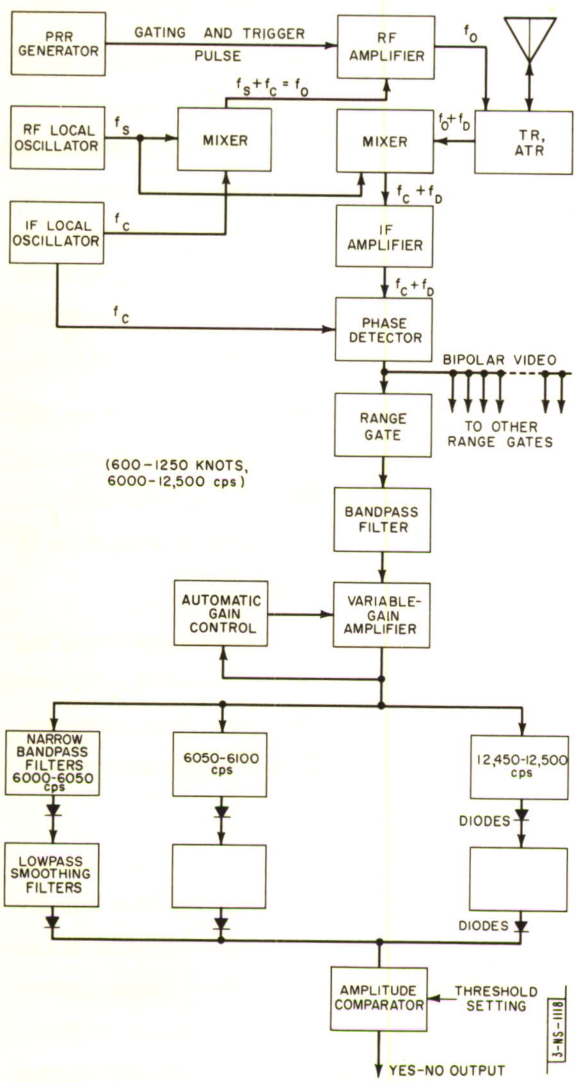

Fig.3E-1. Rudimentary block diagram of high-pulse-repetition-rate system.

A simplified block diagram of this system is shown in Fig. 3E-1. Part of only one range-gate channel is shown, and the tracking channel is omitted as is the repetition-rate control.

The output of the range gate of Fig. 3E-1, with a target present, can be described by Fig. 3E-2. As in all pulse spectra, the picture from $f_D = 0$ to prr/2 is repeated as sidebands about every integral multiple of prr. In the case illustrated, main-beam return is shown at less than own speed, i.e., the antenna is assumed to be looking off the ground track. The bandpass filter would cover the band 6000 to 12,500 cps, corresponding, respectively, to own ground speed (600 knots = 6000 cps when the system is operated at S-band) and prr/2 (12,500 cps is taken here).

The AGC shown following the bandpass filter of Fig. 3E-1 is used to hold nearly

constant the noise-plus-signal power level. This device, including the subsequent filtering scheme, permits the background noise level from whatever source to vary widely, yet provides a fixed threshold at a nearly constant signal-to-noise ratio and false-alarm rate. It is noted that this device may not easily be compared with the theoretically "optimum" threshold signal detector about which much has been written – it is not used here in an attempt to provide such "optimum" performance.

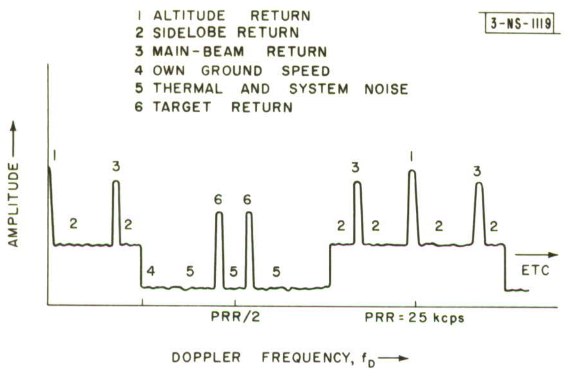

Fig.3E-2. Spectrum of range-gate output.

Lowpass smoothing filters providing post-detection integration are also shown in Fig. 3E-1. Since the target spectral width at S-band is expected to be about 50 cps, narrow-band tuned circuits, 50 cps wide, preceding the diodes, will provide essentially all profitable integration at the predetection level if at least 1/50 sec is allowed as on-target time. The final smoothing filters are used to help stabilize the false-alarm rate for a given constant threshold setting.

The amplifier ("transmitter") of Fig. 3E-1 has purposely been left undefined; it might be a klystron chain, traveling-wave tubes, amplitrons, or some combination thereof. There is some possibility of using an amplitron with low insertion loss as the final stage, allowing TR-ing to be done at low level prior to the amplitron; this would be a development project.

At the selected repetition rate of 25,000 cps, the maximum first-time-around ranging time is 40 μsec, or, allowing ample time for sweep recovery and TR recovery, 30 μsec (about 2.4 nautical miles) is usable. The system has blind ranges, then, the regions of range sensitivity being $n = 3.25$ to $(n + 1) \cdot 2.44$, $n = 1$ to ∞. Blind regions cover the ranges $[(n + 1) \cdot 3.25 - 0.81]$ to $(n + 1) \cdot 3.25$.

Upon receiving an "alarm" while the antenna was scanning, the antenna would stop on target and tracking circuitry would lock-on, establishing accurate position in a range interval. The tracking gates would be similar to those used now in conventional tracking radars and would be capable, therefore, of following a signal with the same order of accuracy. By frequency-modulating (FM-ing) the prr slightly, the location of the target in terms of number-of-times-around can be accomplished. The Doppler signal from a first-time-around target will not move in range; second-time-around targets will move in range by some known value A; third-time-around by 2A; n-time-around

by (n − 1) · A. Targets can be sorted and tracked accurately from these data, though there are probably better arrangements for accomplishing the same result. During track, the prr must be changed continuously and/or periodically in such a way that the target does not disappear in a blind range. The Boeing system of prr-control, described below, does not at present allow highly accurate ranging, although a related method, similar to that described above, should allow accurate ranging.

Use of more than one range channel has been indicated in Fig. 3E-1. Ideally, the range channels (the range gate and everything following it in Fig. 3E-1) should be no greater than one pulsewidth wide. If many range-gate channels are used (and there are attendant advantages), work is needed to arrive at a small, packaged-range channel, perhaps transistorized. It is noted that, although each channel contains many components, most of them are small, light, and passive. Failure of a few of the elements will not affect operation appreciably, other than to slow operation slightly, nor will failure of one or two range-guard channels if several are used. Another "advantage" is that all range-guard channels are identical, simplifying production and maintenance.

Operating with a 2-μsec pulse, a maximum of 15 range-guard channels would be used and the parameters of Table 3E-I might apply.

TABLE 3E-I

PARAMETERS OF ILLUSTRATIVE SYSTEM

Average power	1000 w
Peak power	20 kw
One-way antenna power gain	27 db (40-inch paraboloid)
Wavelength	10 cm
Noise figure	10 db
IF bandwidth	600 kcps
Repetition rate	25,000 cps
Pulsewidth	2 μsec

Using the General Electric radar-range computer, and allowing credit for postdetection integration only, the free-space range on a 2-m^2 target is found to be 25 n.mi. Comparison of the above parameters with those of the present AN/APQ-50 in the absence of clutter and scaling against its performance of 18 n.mi. against F8F and FM-2 targets with a 50 per cent probability of detection (these are experimental data), it is found that a range of 30 n.mi. can be expected of this pulse-Doppler radar against the same targets.

It is noted that these ranges – automatic detection and lock-on – should be obtained in the presence of interfering clutter at least 30 db, and possibly as much as 70 db, greater than the signal, for forward-hemisphere attacks.

The system just described admittedly requires many components – with 15 range-guard channels and 50-cps bandpass filters followed by postdetection integrators, a total of 1950 bandpass filters, 1950 lowpass filters and 3900 diodes. Most of these are small, light and essentially passive elements. It is also found, however, that for 1/50 sec on target and still using 50-cps bandpass filters, and using three 10-μsec range-guard channels instead of 15 two-μsec channels, the count is now reduced to 390 narrow-band filters, 390 smoothing filters and 780 diodes at the cost of about 33 per cent in range and some flexibility. The latter are reasonable numbers of components – the optimum answer to this question, however, is probably neither of the two just described, but some other combination resulting in a final range performance close to that calculated above. The basic parameters given above are conservative; if range must be sacrificed to reduce complexity, some of it can be regained by use of higher powers and better noise figures. To illustrate that 780 filters and diodes are not excessive: the Rayspan high-speed spectrum analyzer now does approximately the same operations required in this system, using 400 filters in a package about one cubic foot in size and 20 pounds in weight. It is expected that future developments along this line, using perhaps magnetic drums to include postdetection integration, will encompass wider ranges of parameters in essentially the same size and weight.

With regard to using this radar in other than forward-hemisphere attacks, i.e., the Doppler region between $f_D \approx 300$ cps and own ground speed as shown in Fig. 3E-2:

> Filters to cover the band are required.
>
> It is probable that, having once locked on in a forward-hemisphere attack, track can be maintained down through own ground speed and into the sidelobe return, particularly at high altitudes where sidelobe return is low. (The lower the sidelobe level, the lower the altitude at which this performance can be expected.) A notch filter driven by a computed function of ground speed and antenna relative azimuth, primarily, would be used to delete the main-beam return. This would create a tracking problem similar to tracking through the "altitude circle" in a conventional radar. Memory circuits help to alleviate this problem. It is noted here that this and any other radial-velocity-sensitive radar cannot track when the radial velocity is zero. Here again, memory circuits are of assistance.
>
> It is possible that, although considerable development may be necessary, all-angle attacks at all altitudes can be made. Techniques similar to those described above would be applied,

> plus the equivalent of spectrum analysis of clutter return due to sidelobes to sort out the target – which gives a more highly coherent return. Performance in rear-hemisphere attack at low altitude would be degraded; the expected range might be half (an estimate) that at high altitude or forward hemisphere, and considerably slower search might be necessary. It is fortunate that rear-hemisphere attacks allow more time for acquisition.

If eventually it is found possible to acquire and track in the clutter return, the radial-velocity coverage of this system will be approximately 30 to 2470 knots. At high altitudes where clutter is not troublesome, this performance can be expected.

BOMARC SYSTEM

Boeing has for several years worked on an X-band pulse-Doppler radar for eventual use as the Bomarc target seeker, operating automatically in acquisition and track for closing speeds up to the Mach 3 region. A breadboard system has been constructed, and flight tests in a C-47 are now being run. In general, the system is similar to that just described; some of the differences will be mentioned here.

The present breadboard system operates at about 400 watts average power, a duty cycle of one-third, a repetition rate of 125 to 250 kcps, and at X-band. The narrowest pre-detection filter bandwidth is (or is planned to be) 300 cps. In the search mode, a repetition rate f_R of 125 kcps is used. Upon receiving an alarm, the target must obviously be in the 4-μsec available ranging interval which is followed by two range channels – roughly the equivalent of two channels such as shown in Fig. 3E-1. At this stage, effectively nothing is known about the target's range. (Range is not really necessary in the Bomarc seeker.) Boeing proposes the following method to derive range if it is needed.

After acquiring the target as above, while closing on the target, it is necessary to change f_R in such a way that the target will never lie in a blind range – whether or not one wishes to measure range. Boeing proposes to use, and has built, an automatic pulse-repetition-frequency control (APRFC) which, after the target is acquired at an unknown range X (see Fig. 3E-3) and at f_R = 125 kcps, controls f_R in such a way as to keep the target centered between transmitted pulses. In so doing, the APRFC controls f_R as shown in Fig. 3E-3. Applying some algebra, it is found that:

$$R = -(\lambda f_R/2)\,(f_D/\dot{f}_R) \quad ,$$

that is, range is proportional to the operating wavelength, the repetition rate and Doppler frequency at the instant in question, and inversely proportional to the time derivative of the repetition rate. The first three are supposedly known and $\dot{f}_R$ can be determined by differentiating the action of the APRFC. Because of system noise, it is difficult to determine the range exactly; selection of the proper range interval in terms of number-of-times-around ± 1 is possible. Other methods, such as described for the preceding system, should lead to better range measurement if required.

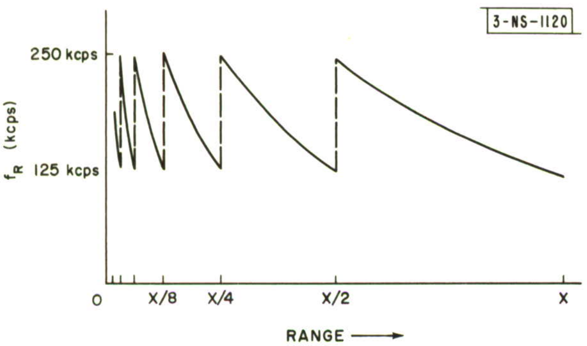

Fig.3E-3. Repetition-rate changing (Boeing system).

Under consideration is use of two repetition rates during acquisition, in proper ratio to uneclipsed blind ranges in the region where the probability of detection becomes very high.

As a result of the high repetition rates and short range intervals involved, it becomes important to decrease TR recovery time as much as possible. Boeing reports success here, reducing TR recovery to the order of one μsec.

Boeing is also considering a long-range search set operating on similar principles. Higher power level, very slow scan time, large antenna, S-band, etc., would be used. It is understood that little or no laboratory work has been done on this radar to date.

Experimental performance data on the low-power breadboard target seeker now installed in a C-47 by Boeing should soon be available and could serve to confirm or deny and correct the range performance predicted above.

Radars of this same general type might also be applied to land- and ship-based fire control.

T.R. Silverberg

CHAPTER 4

SURFACE-TO-AIR RADARS

CHAPTER 4
SURFACE-TO-AIR RADARS

INTRODUCTION

Air defense systems, both existing and proposed, rely heavily on radar information for warning, general surveillance, tracking, and intercept control. The functions of the radars considered in this chapter may be listed as follows:

Prime radars for interceptor guidance,
Gap fillers for low altitude coverage,
Height finders,
Texas Tower radars,
Picket ship radars,
Automatic-alarm radars for DEW and BUK lines,

Some general statements can be made about the requirements for these radars. The threat for the 1960 period envisages attacks that may comprise large numbers of bombers in mass raids. These may fly at all altitudes up to 60,000 feet, with velocities of 600 knots, and the bombers may exhibit radar cross sections of only a few square meters. The large amount of data to be handled militates against the use of manual control and may require machine-controlled interception as exemplified by the SAGE System. The radars must provide the desired low- and high-altitude coverage on small targets, and supply data of sufficient precision to permit carrying out interceptions at high speeds.

Though this chapter is not particularly concerned with the deployment of the radars in question, it appears that, of the several possible arrangements, the use of long-range radars for the high-altitude cover, with numerous gap fillers to provide low-altitude cover, is a desirable choice for many situations. With this system in mind, the performance of the radars is discussed.

Perhaps the weakest point of the entire radar system is its vulnerability to jamming by equipment that may be carried by the enemy at small cost. Many of the recommendations made herein are directed toward the reduction of this menace. Two methods will be discussed. The more important of these is the employment of a wide diversity of frequencies, both in the present radar bands and at new frequencies, together with tunability of each radar over a wide band. This makes it necessary for the enemy to carry a complex of jammers, and to spread the power of each over a wide spectrum.

TABLE 4-I

PLANNED AIR DEFENSE RADARS

	FPS-3 MPS-7	CPS-6B	TPS-10	FPS-6	FPS-8 MPS-11	FPS-3/ GPA-27
Frequency (Mcps)	1220-1350	2700-3020	9230-9400	2700-2900	1280-1350	1250-1350
Peak power (Mw)	0.5 (2 beams)	0.7 (5 beams) 1 (1 beam)	0.25	5	1	2
Pulselength (μsec)	3, 6	I, 2	0, 5, 2	2	3	6
Repetition rate (pps)	400, 200	600, 300	540	360	360	360
Noise figure (db)	12	12	13	9.5	10	
Scan rate (rpm)	5	2 - 15	-	-	0 - 10	6.6
Antenna size (ft)	40 × 16	25 × 10 (V-beam)	3.7 × 10	7.5 × 30	25 × 14	40 × 16
Horizontal beam-width (deg)	1.3	1	Height finder	Height finder	2.5	1.3
Antenna gain (db)	37	40 (1st Beam)	42	39	30.5	34
75% blip-scan range (n.mi.)						
B-47	130	120	50	120	60	175
B-29	210	180	90	180	110	280

Having thus reduced the power-per-unit-frequency of the jammer, it becomes possible to build radars of extreme power and large antenna size, which retain a degree of effectiveness even in the presence of jamming.

RADARS FOR SPECIFIC FUNCTIONS

GCI Radars

There are presently in operation in the continental United States some 75 radar installations which comprise the primary control system for defense of this country against air attack. The long-range radar in use in the majority of these sites is the AN/FPS-3. The coverage diagram for this set is shown as the inner curve of Fig. 4-1. It is evident that the high-altitude performance of this radar falls far short of the 60,000 foot level set by the anticipated threat. A modification kit (AN/GPA-27) for the radar has been designed which will increase the coverage to that given by the outer curve. The major characteristics of these and other radars discussed here may be found in Table 4-I.

Development of the modification kit is nearly complete, but a contract for its production has not yet been placed. It is urged that production be started without delay.

The characteristics of the modified FPS-3/GPA-27 appear to fit well the requirements of the SAGE System. The interdependence of the control radar and the AI radar characteristics in determining the outcome of an attempted interception has been dealt with in some detail in Chapters 2 and 3 and in their appendices. It will suffice to state here that AI lock-on range is a very sensitive parameter, and that satisfactory results under difficult conditions will be achieved only when the AI lock-on range exceeds 10 miles. If ranges of this magnitude can be assumed, then the beamwidth, pulse-length and data rate of the GPA-27 will be adequate for control of interceptions even

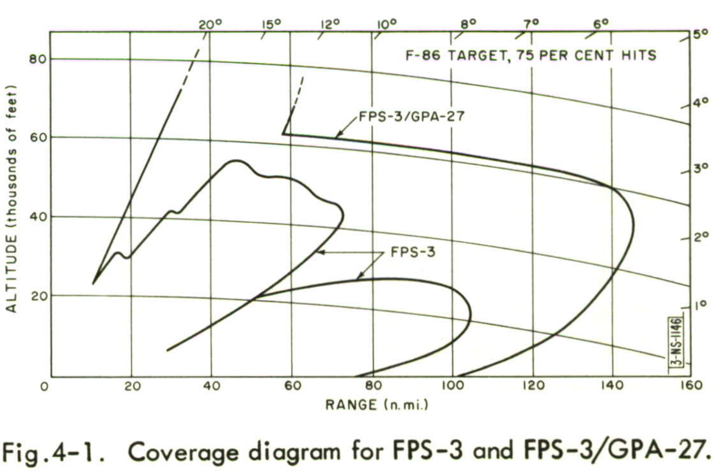

Fig.4-1. Coverage diagram for FPS-3 and FPS-3/GPA-27.

under the difficult conditions of forward-hemisphere attacks against bombers capable of 1-g turns.

Except for vulnerability to jamming, the planned long-range radar program appears adequate. When jamming is considered, however, it is apparent that the entire system can break down completely through the employment by the enemy of relatively simple countermeasures. There are planned for each radar site two transmitters, each tunable ±4%. Tuning to a new frequency requires about 15 minutes. Switching between transmitters can be done in 15 seconds. The ability to switch frequency reduces greatly the effectiveness of spot jamming, so that the enemy will be forced to barrage jamming with noise distributed over the entire tuning band.

The self-screening range, i.e., the range beyond which the radar return is less than the power received from the jammer, can be shown to vary in the following manner:

$$R_{ss} = \left(\frac{P_R}{P_J} \frac{G_R}{G_J} \frac{\tau \sigma}{4 \pi (S/N)}\right)^{\frac{1}{2}} ,$$

where

R_{ss} = self-screening range (nautical miles),

P_R = peak power of radar transmitter (Mw),

τ = pulselength (μsec),

G_R = gain of radar antenna,

G_J = gain of jammer antenna,

σ = echoing area of target,

S/N = minimum signal-to-noise ratio required for PPI detection, a function of hits,

P_J = jammer power (w/Mcps).

A jamming power of 5 watts per megacycle can be generated over the FPS-3 tunable band with equipment that need not weigh more than a few hundred pounds. When this countermeasure is employed against the modified FPS-3, a self-screening range of about 10 miles can be anticipated, reducing the radar net to impotence. Examination of the self-screening equation shows that range can be bought back only by increasing the energy per pulse, increasing the antenna gain, and performing better integration on the signal. Large improvements in these factors are necessary before reasonable ranges are attained. A fuller discussion of this subject is contained in Appendix 4-A.

The jamming threat can be partially overcome by making the process of jamming a costly one for the enemy. This can be accomplished best by frequency diversity – using many widely spaced frequencies so that a multiplicity of jamming equipment must be carried by the enemy. To this end, we recommend the employment of several independent radars at each radar site, operating on frequencies chosen to provide as wide a diversity as possible. It is urged that new frequency bands not now used for continental air defense be established, so that the new equipment, together with that of present and planned installations, would give a multiplicity of frequencies to be countered by jamming. Suggested new bands are: 223, 435, 600, 900, and 5600 megacycles. Development of suitable components for these frequencies should be initiated as soon as possible.

The limit of radar performance against jammers has not been reached in existing search radars. The energy per pulse can be greatly extended by using higher peak powers and longer pulselengths; and antenna gains can be increased by using larger antennas. The cost of a radar set per se is now a small fraction of the cost of a radar site, when one considers building, roads, communication, processing equipment, land lines and the charges for operating and maintenance personnel. Because of this, and when faced with the threat of complete impotence in the face of jamming, it is reasonable to provide the largest and most powerful radars that technology permits.

In Appendix 4-A are described some large radars that could be built without requiring any unusual or untried techniques. As an example, a 435-Mcps radar with an antenna 120 feet long by 40 feet high, using a 20-Mw pulse of 20-μsec duration would have a free-space range on a 2-m^2 target of 2400 miles. Were this target to carry a jammer producing a power as great as 40 watts per megacycle, the radar would be able to determine the range of the target out to a distance of 34 miles. Arguments are given in the appendix to show that, in all probability, the assumptions leading to this self-screening range are very pessimistic and that much greater ranges actually could be expected in the face of jamming. For routine surveillance and until jamming actually starts, sets could be operated with lower peak power and shorter pulselengths.

The use of jamming by the enemy does not prevent us from obtaining information about his azimuth and height. By correlating such information received at many different sites, it is possible to determine the positions of the jammers if not too many are in operation. The difficulties in correlation increase both with beamwidth and with spurious responses from sidelobes: accidental coincidences increase with beamwidth; ambiguities are difficult to resolve when spurious responses from sidelobes are present. Narrow beamwidth and very low sidelobe levels both can be attained by the use of large

antennas and high frequencies (such as C-band); for this purpose care will be needed in shading the illumination for best sidelobe suppression. A number of C-band radars have been recommended so that the enemy will be forced to operate jammers on a frequency that is most useful to us for the purpose of these correlation techniques.

Gap Fillers

To provide low-altitude cover below the horizon lines of the long-range radars, it is planned to install automatic-alarm radars with relatively short range and altitude coverage, the data from which are relayed back to the direction centers of the SAGE System. To obtain solid cover over the desired area, about 900 such installations will be required. Two radar transmitters are used at each site, with automatic change-over provided. The present FPS-14 appears to be adequate for the purpose, except for its susceptibility to jamming.

Because of the relatively large number of radars required, and because no personnel are expected to be in attendance, it is not considered desirable to use a multiplicity of sets at each site to achieve frequency diversity. Instead, it is recommended that sets on different bands be used at the different sites, leaving a limited capability in the net if one or two of the bands are jammed. It is desirable that the frequencies chosen be distinct from those used in the long-range radars in order to further increase the complexity and weight of the jamming equipment that the enemy must carry. Because of the short ranges required of gap fillers, weather clutter is not seriously significant; hence the following frequencies are recommended: 5650 Mcps (C-band), 3500 Mcps and 2880 Mcps. Location of targets by cross-correlation of azimuth information is considerably less difficult than in the case of the long-range radars because of the close spacing of the gap fillers. It is suggested that techniques for accomplishing this correlation be developed and that no attempt be made with these to obtain range by going to very high power and large antennas.

Height Finders

The existing or planned height finders are the FPS-6 and TPS-10 nodding-beam radars, and the FPS-7 stacked-beam radar which is a combined search and height finding set. At least two nodding-beam radars are required at each long-range radar site in order to handle large numbers of tracks. The capabilities of these sets, while limited at the low altitudes, appear to fulfill the requirements in a satisfactory manner. At the same time, their frequencies (9300, 3500 and 1200 Mcps) complement those recommended for the search and the gap-filler radars in providing further extension of the diversity

principle. It seems necessary then only to make sure that all three types are used. It is believed that, in the presence of jamming, these radars will be able to obtain elevation angle on a noise signal; it is suggested that tests be made to insure that this is possible. Elevation angle from these radars can be correlated with range information from the long-range radars to obtain height data.

The height-finder radar offers an opportunity for raid evaluation as will be pointed out in Appendix 2-A. It is recommended that height finders be designed so that repetition rates of 1500 pps or more can be employed in order that listening techniques be effective.

Radars for Texas Towers

The same arguments that have dictated the use of several high-power radars at the land sites apply with equal cogency to the Texas Towers. In addition, since these are the last fixed radars to seaward, extreme ranges are highly desirable to provide high-altitude warning and control when weather conditions are such that picket ships and AEW craft are unable to operate effectively. While space limitations do not permit the freedom of choice that the land sites offer, and it may be necessary to incorporate two or three antennas in a single radome, it is recommended again that several very-high-power sets on different frequencies be used. Fuel consumption need not be inordinate, since the sets can be run at much reduced power if they are not being jammed. Appendix 4-B describes some suggested radars for this purpose.

Radars for Picket Ships

The function of a radar picket ship is no different from that of a Texas Tower or a land-based radar site – it is a means to locate radars at points where it is impractical to construct platforms rigidly attached to the earth. The pickets are to be used for intercept-control functions as well as for early information. The nature of the platform of course imposes certain restrictions on the type of radar that is practical; we view the picket ship simply as a somewhat unsteady platform on which to build a radar.

The virtues of large antennas for search radars have been pointed out in some detail in Chapter 2. In relation to picket ships, a plausible stopping point (which should not be regarded as an upper limit) for a rotating antenna is to make its horizontal dimension slightly less than the width of the ship. For a Liberty ship, this implies an antenna width of 45 feet. Considerations of beamwidth, surface reinforcement, and precipitation echoes lead to choice of a relatively low frequency. To complement the 425-Mcps radars proposed for the AEW function, a frequency of 600 Mcps is suggested.

The accuracy and continuity of coverage required of the radar for control purposes makes stabilization of the antenna against pitch and roll highly desirable. From a radar standpoint, there is no particular reason to mount the antenna high above the deck, while it is obviously desirable for stability to keep the mass as low as possible. It may be necessary to remove or lower masts, funnels and other projecting objects so that proper performance of the antenna, both mechanical and electrical, can be achieved.

It is recommended that two such large antennas, mounted back-to-back on the same stabilized pedestal, be provided. One of these would be for the 600-Mcps set, the other for a 1200-Mcps stacked-beam search and height-finding set similar to the SPS-2. The use of a radome to shield the antennas from wind loading may greatly simplify the stabilization mechanism. While there are many problems associated with shipborne radomes, recent success in the arctic with pressurized balloon-type structures indicates that serious consideration should be given to their use on board ship.

A separate nodding-beam height finder on 5650 Mcps, having long-range height-finding capability, as well as capability for raid-size evaluation by listening, is recommended to complete the search and control radar complement.

The characteristics of the radars that have been recommended are discussed in more detail in Appendix 4-B.

Early-Information Radars

Radars that are programed for installation in the DEW Line are modifications of the TPS-1D radar, using M-33 antennas and fitted with automatic alarm-ringing circuits. For low-altitude cover, a CW Fluttar network is planned.

The function of an early-information net differs considerably from that of the nets that have been considered earlier. In particular, jamming is of much less concern; since detection is a primary function and tracking a secondary one, the employment of jamming by the enemy would imply increased detection range and certain identification as hostile. As a result, there is no particular compulsion toward extreme power and frequency diversity in the radars planned for these early-information nets.

The DEW Line radar is not an ideal radar for the purpose. As shown in Fig. 4-2, its coverage is spotty, especially on high-flying targets. Nevertheless, in view of the

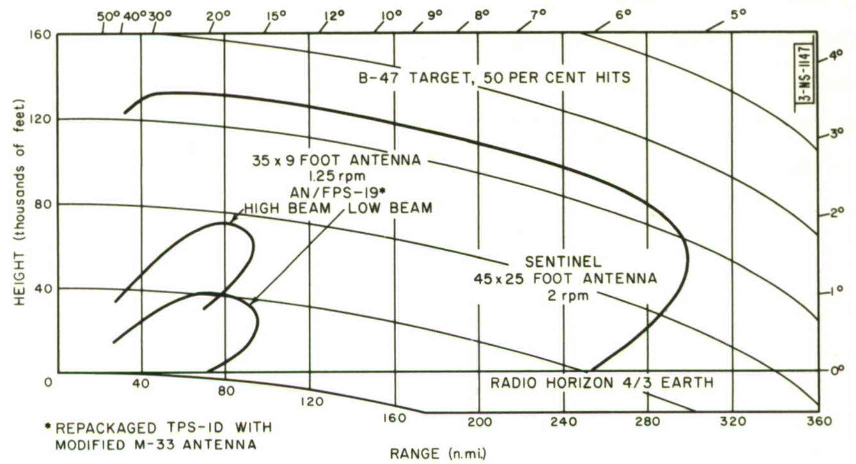

Fig. 4-2. Coverage diagram for FPS-19 and Sentinel radars.

desirability of immediate construction of the DEW Line, the programed radars are endorsed for the first installations.

A radar with a considerably enhanced coverage, and more freedom from false alarms, is represented by the Sentinel now under construction at Lincoln Laboratory. Its coverage is also given in Fig. 4-2. The 45 × 25 foot antenna will fit in existing radomes. It is recommended that, in future installations, consideration be given to improved radars of this type which will provide much better high-altitude coverage.

THE RADAR ENSEMBLE

In detailing the types of radars considered desirable for the various functions, emphasis has been placed on tunability, frequency diversity, and (in some cases) high power as measures to be taken to reduce susceptibility to jamming. The significance of frequency diversity can best be appreciated by viewing the various radars as an ensemble. Table 4-II illustrates an arrangement of radars according to the recommendations given here. The listing is made up in columns by frequency, comprising 9 distinct well-separated bands, each of which would require a separate wide-band jammer. In the body of the table are listed the proposed radars, each row representing a particular installation or site. Many of the sets listed are now available, and only proper dispersal is required to gain the desired effect. The high-power search sets exist, if at all, only as experimental gear, and their development and procurement represents a substantial task. It is on these latter radars, however, that our chief reliance is placed; without these, many of the remaining sets

TABLE 4-II

THE RADAR ENSEMBLE

Function	Frequency (Mcps)								
	9300	5650	3500	2880	1200	900	600	435	223
AEW&C	APS-45	Height finder		APS-20 Stacked-beam				Search	
DEW line					FPS-19		Sentinel	Fluttar	
Picket ship		Height finder			Stacked-beam Search and height		Search		
GCI site 1 (or Texas Tower)	TPS-10 Height finder		Search and listen		FPS-3/GPA-27		High power		High power
GCI site 2		Search and listen	FPS-6 Height finder		FPS-3/GPA-27	High power		High power	
GCI site 3			FPS-6 Height finder	Search and listen	FPS-7 Search and height	High power			High power
Gap filler 1		Gap filler							
Gap filler 2			Gap filler						
Gap filler 3				FPS-14 Gap filler					
AI	Pulse			Pulse					
	APG-43			Pulse Doppler					
Nike	Tracking			Acquisition					

would be quite useless. Therefore every effort should be made to have these sets in operation at the long-range radar sites as soon as possible.

SURFACE-TO-AIR RADARS FOR MERCHANT SHIPPING

Lamp Light proposals for a defense system provide for general information on the presence of aircraft over the seas by utilizing merchant shipping for surveillance. The requirements placed on a radar for this purpose are analyzed in Appendix 4-C from the standpoint of the statistical probability of obtaining the desired number of reports as a function of the range of the radar and the number of ships outfitted. It is found that a relatively modest (20-mile) range performance will do a good job if the average spacing of equipped ships is about 100 miles. The number of such ships at sea in the North Atlantic would thus be of the order of 300.

A radar with this range capability and high-altitude coverage can be patterned after the Lincoln Laboratory Chipmunk II, and is described in Appendix 4-D. The radar operates at 425 Mcps and can be packaged in a small box. The antenna would be about 7 × 7 feet. Operation of the radar is completely automatic; the presence of a target causes an alarm to ring, and indication of the range and azimuth is provided by signal lights. The power is sufficiently low and the frequency such that conventional radio circuitry is employed; a high degree of reliability and freedom from frequent maintenance can be expected.

If a large number of vessels of a wide variety is to be used for general sea surveillance, an automatic-alarm radar similar to that described is indicated.

RECOMMENDATIONS

For the near period, it is recommended that the long-range radar sites be outfitted with the modified FPS-3/GPA-27 radars as programed. The susceptibility of these radars to jamming requires that drastic measures be taken to diminish this threat. Two principles are basic to the recommendations for future implementation that follow: frequency tunability and diversity to force the spreading of jamming power thinly over the spectrum; and excess performance to maintain a reasonable capability even in the presence of jamming.

Frequency diversity has been employed for all situations, so that each type of radar (long-range, gap filler, picket ship, height finder, etc.) is represented by several frequencies, and the ensemble occupies 10 frequency bands. Two new frequency bands, 600 and 900 Mcps, are proposed. Tunability is incorporated in each radar to avoid concentrated spot jamming.

At the long-range radar sites in the air battle region, it is recommended that at least 3 control radars be employed, and that these be large high-power radars capable of operating at limited range against barrage jammers delivering several watts per megacycle. While each site would have search radars on 3 frequencies, the same set of frequencies will not be used at adjacent sites.

A capacity for listening to jammers to obtain precision azimuth data should be incorporated into each site. Correlation techniques must be developed to permit unambiguous determination of target position.

Height finders are also to be diversified in frequency, 3 frequency bands being used, with at least two height finders at each site.

Gap-filler radars would occupy a single band at each site; however, radars in 3 different bands would be used, and selections made from these to outfit the sites.

It is recommended that similar principles be employed in selecting radars for Texas Towers.

It is recommended that picket ships carry two main radars, a 600-Mcps set using a 45 × 25 foot antenna, and a 1200-Mcps stacked-beam search and height-finding set using a similar antenna mounted back-to-back with the first. A C-band height finder for auxilliary use completes the major radar equipment.

There appears to be no urgent necessity for maintaining full capability against jamming in the DEW lines, since the primary function of the lines is not thereby disturbed. Radars with performance characteristics considerably enhanced over those now planned can be made available in the near future, and it is recommended that later installations make use of recent advances in the design of automatic-alerting radars.

CHAPTER 4 RECOMMENDATIONS

1. *For the near term we recommend, as the basic GCI radar for the long-range radar sites, the modified FPS-3/GPA-27 set.*

2. *We recommend a long-term program aimed at reducing the jamming threat by frequency tunability and diversity, and by using very large antennas and very high power output.*

3. *To provide frequency diversity, we recommend a radar ensemble that occupies altogether 10 frequency bands. Each type of radar (long-range, GCI, gap filler, height finder, etc.) is to be represented by several frequencies, each radar is to be tunable, and new frequency bands are proposed at 600 and 900 Mcps.*

4. *For long-range radar sites–the most critical areas–we recommend the use of at least three control radars of very high power with very large antennas capable of operating at limited range against barrage jammers delivering several watts per megacycle. Adjacent sites would not use the same three frequencies.*

5. *For each site, we recommend at least two height finders similarly diversified in frequency.*

6. *We recommend tests to determine whether height-finding radars are able to obtain elevation angle on a jamming signal.*

7. *To permit the use of listening techniques for raid evaluation, we recommend that height finders be designed so that repetition rates of 1500 cps or more can be employed.*

8. *At each gap-filler site, we recommend the use of two radar transmitters with automatic changeover. These two transmitters would operate on the same frequency, but adjacent sites would use different bands.*

9. *We recommend that each site be provided with a capacity for listening to jammers to obtain precision azimuth data. Correlation techniques must be developed to permit unambiguous determination of target position.*

10. *We recommend that picket ships carry two main radars, a 600-Mcps set using a 45 × 25 foot antenna, and a 1200-Mcps stacked-beam search and height-finding set using a similar antenna mounted back-to-back with the first. A C-band height finder is desirable for auxiliary use.*

11. *For radars for early-information lines, frequency diversity and extreme power are less important, but we recommend that later installations take advantage of recent advances in automatic-alerting radar design to provide enhanced coverage and greater freedom from false alarms.*

APPENDICES TO CHAPTER 4

APPENDIX 4-A
ANTI-JAMMING MEASURES FOR SURFACE-TO-AIR RADARS

Surveillance radars can be designed to meet the foreseeable future basic requirements of continental air defense. However, when the possibilities of electronic countermeasures are considered, there are no existing or planned radars that measure up to the threat. Electronic jamming is believed to be the most serious countermeasure that could be employed against our radar net because it now appears possible for each penetrating bomber to barrage-jam in several bands, and to screen itself to a small fraction of the nominal radar range, by carrying one or two thousand pounds of jamming gear. This jamming capability is made easier by the development of the Carcinotron, a wide-band, voltage-tunable tube. The nature of this countermeasure and its effects on radars, together with a summary of possible anti-jamming measures, is given in Chapter 9.

The following measures are effective in improving radar performance in the presence of jamming:

> Enforce barrage jamming by making radars rapidly tunable over the widest possible band, and by using several bands throughout the radar net.
>
> Increase the radar transmitting antenna gain as much as possible consistent with the basic data requirements, and at the same time reduce receiving-antenna sidelobes as much as possible.
>
> Transmit high-energy pulses (high peak power and long pulses) so as to illuminate the target more strongly.
>
> Employ techniques for "digging" signals out of noise.

(It is evident that improved receiver noise factor is of no use in improving the radar performance in the presence of jamming.)

The effectiveness of these measures can be understood by inspection of the jammer self-screening range* equation:

$$R_{ss} = \left[\frac{P_R}{P_J}\,\frac{G_R}{G_J}\,\frac{\tau\sigma}{4\pi\,(S/N)}\right]^{1/2} , \tag{1}$$

*The self-screening range is the range within which the signal-to-jammer power ratio is great enough for target detection.

where

R_{ss} = self-screening range (nautical miles),

P_R = peak power of radar transmitter (Mw),

τ = pulselength (μsec),

G_R = gain of radar antenna,

G_J = gain of jammer antenna,

σ = echoing area of target,

S/N = minimum signal-to-noise ratio required for PPI detection, a function of hits,

P_J = jammer power (watts/Mcps).

The self-screening range and the anti-jamming measures listed above indicate the favorable directions in radar design, but it still remains to be seen whether the best that can be done is adequate to meet the jamming threat. The following argument will show that drastic but feasible changes in radar design can result in a continental air defense radar net that should perform well against an extreme version of the jamming threat.

The weight of a Carcinotron jammer or group of jammers is very nearly proportional to the width of the band jammed and the power per unit frequency, i.e., $W = cBP_J$, where W is the jammer weight, B the bandwidth jammed and c the weight per unit power. When this relation is substituted for P_J in Eq. (1), the self-screening range is

$$R_{ss} = \left[\frac{cBP_R}{W}\ \frac{G_R}{G_J}\ \frac{\tau\sigma}{4\pi\,(S/N)}\right]^{1/2} \quad . \tag{2}$$

Assume that each major radar installation contains n radars in widely separated wavelength bands and that the transmitting gain is independent of wavelength, i.e., that the radars are all designed for the same angular coverage regardless of antenna size. Assume further that R_{ss} is independent of wavelength, i.e., that the enemy seeks essentially the same coverage in each band jammed. Finally, assume that the target carries n jammers, one covering each of the radar bands, and that he distributes his power so as to minimize the self-screening range. He accomplishes this objective when

$$R_{ss_1} = R_{ss_2} = \ldots = R_{ss_n} = R_{ss} \quad , \tag{3}$$

because the self-screening range of the ensemble of jammers is the self-screening range of the least effective jammer. In distributing his jamming power, the enemy must keep the total jammer weight constant, that is,

$$\sum_{i=1}^{n} W_i = W_1 \quad . \tag{4}$$

Rewriting Eq. (2),

$$W_i = \frac{cB_iP_{R_i}}{R_{ss}^2} \frac{G_R}{G_J} \frac{\tau_i \sigma}{4\pi (S/N)} \quad . \tag{5}$$

Collecting the wavelength-invariant factors,

$$W_i = \left[\frac{c\sigma G_R}{4\pi R_{ss}^2 (S/N) G_J}\right] \left[B_iP_{R_i}\tau_i\right] \quad . \tag{6}$$

Then, combining Eqs. (4) and (6),

$$W = \left[\frac{c\sigma G_R}{4\pi R_{ss}^2 (S/N) G_J}\right] \sum_{i=1}^{n} B_iP_{R_i}\tau_i \quad , \tag{7}$$

and the optimum self-screening range against the ensemble of radars is

$$R_{ss} = \left\{\left[\frac{c\sigma G_R}{4\pi W (S/N) G_J}\right] \sum_{i=1}^{n} B_iP_{R_i}\tau_i\right\}^{1/2} \quad . \tag{8}$$

It is instructive to calculate the optimum self-screening range for a "maximum" threat against a realizable ensemble of radars. It is assumed that the practical limits on jammer weight for the foreseeable future will be reached when each bomber carries 10,000 pounds of jamming equipment. This weight is equivalent to the entire bomb load of a B-47 flying a standard mission. The best estimates available are that jammer specific weights will be one pound per watt of jamming power. The maximum jamming threat is thus characterized by the values W = 10,000 lb and c = 1 lb/watt. It is assumed further that $G_J = 1$, $G_R = 10{,}000$, $\sigma = 2$ square meters and $(S/N) = 4$. Then

$$R_{ss} = 0.20 \left[\sum_{i=1}^{n} B_iP_{R_i}\tau_i\right]^{1/2} \quad . \tag{9}$$

In the family of radars listed in Table 4A-I, the values of B_i, P_{R_i}, and τ_i are considered to be well within the present radar art at each of the wavelengths. Table 4A-II summarizes all the main parameters of these radars. Applying Eq. (9) to this set of

TABLE 4A-I

RADARS FOR JAMMING CALCULATIONS

Radar	Wavelength λ (cm)	Bandwidth B (Mcps)	Peak Power P_R (Mw)	Pulse Duration τ (μsec)
1	135	50	20	20
2	70	60	20	20
3	50	70	15	15
4	33	80	10	10
5	25	100	10	7
6	10.7	300	4	5
7	8.6	350	4	5
8	5.5	500	3	5

radars, the combined self-screening range for the threat considered is 34 miles. This range is, of course, inadequate but at the same time offers some hope of meeting a realistic jamming threat, as contrasted to the present and planned radars which would have essential zero self-screening range. It must be recognized that the preceding calculations are somewhat pessimistic for the following reasons:

The assumed target cross section of 2 m^2 is conservatively chosen.

It would be virtually impossible for an enemy to achieve the optimum distribution of power required.

The lower-frequency radars can achieve up to 6 db better performance than the calculations show – equivalent to doubling the self-screening range – by use of surface reinforcement.

No account has been taken of integration, velocity filtering, etc., which can reduce the signal-to-noise ratio for detection.

The weight of jamming equipment postulated in the calculation is approximately seven times the weight of the present complement of jamming equipment used in the B-47, and is thus a possible but improbable threat.

Of course, the jamming threat will continue to grow, as larger bombers become available to the enemy and as more efficient ways are devised to generate microwave noise.

TABLE 4A-II								
POSSIBLE HIGH-POWER RADARS								
	1	2	3	4	5	6	7	8
Wavelength (cm)	135	70	50	33	25	10.7	8.6	5.5
Frequency (Mcps)	223 ± 25	425 ± 30	600 ± 35	900 ± 40	1250 ± 50	2800 ± 150	3500 ± 175	5500 ± 250
Peak power (Mw)	20	20	15	10	10	4	4	3
Pulselength (μsec)	20	20	15	10	7	5	5	5
Repetition rate (pps)	300	300	300	300	300	300	300	300
Noise figure (db)	4	5	6	7	8	9	10	12
Scan rate (rpm)	6.6	6.6	6.6	6.6	6.6	6.6	6.6	6.6
Antenna size (feet)	240 × 80	120 × 40	90 × 25	60 × 17	45 × 13	18 × 6	15 × 5	10 × 3
Horizontal beam-width (degrees)	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2
Antenna gain (db)	40	40	40	40	40	40	40	40
Maximum range on 2-m^2 target (miles)	3400	2400	1800	1200	870	320	280	240
Self-screening range (miles)	34	34	34	34	34	34	34	34
Jamming power (watts/Mcps)	40	40	22.5	10	7	2	2	1.5

However, radars can continually be made less susceptible to jamming. Improvement in the combination of techniques for obtaining higher average radar power, more effective target integration, and higher transmitting antenna gain can and must keep up with improvement in enemy jamming capability.

D.J. Crowley

APPENDIX 4-B

RADAR PROGRAM FOR PICKET SHIPS AND TEXAS TOWERS

The defense system proposed by Project Lamp Light makes use, in its seaward extension of contiguous coverage, of a combination of AEW and surface-based radars. Some of the picket ships will be used also for ASW and for communication, and these may require compromises, but those picket ships whose only function is aircraft detection should have the best available radars. This appendix will outline parameters for picket-ship and Texas Tower radars to supplement and extend the shore-based radar net and to carry seaward the same philosophy as was used in design of the ground radars.

The important objectives fulfilled by the recommended program are:

Multiple radar-frequency bands,

Tunability within each band,

Optimum volume coverage on each frequency,

High average transmitter power – as high as the state of the art will allow with reliability.

It will be observed that enemy jamming is the predominant threat to be countered; but, at the same time, adequate radar data are to be obtained for intercept control. In other words, data rate, pulselength, beamwidth, vertical coverage, and detection range must be maintained. Resistance to jamming, while of extreme importance, must be viewed in the context of radar design for combat aircraft.

In the recommendations that follow, certain general requirements apply to picket ships. These are:

Antenna height is not important but, to minimize the moment above the water line, the height should be small.

The enemy should encounter many radar frequencies regardless of the route he chooses, hence two radar frequencies should be used for ship air-search radar, and these should be different frequencies than are used for AEW and on Texas Towers.

The primary function of the ship and its radar is such that detection and tracking, with 360° solid azimuth coverage on targets at all altitudes up to 60,000 feet is necessary, hence obstructions such as the stacks must either be moved below and away from the antenna or the antenna must be mounted high enough for a clear view.

In Table 4B-I listing frequencies and other parameters for Texas Towers and picket ships, the assumption is made that the enemy will have to jam all radars – AEW and

TABLE 4B-I						
RECOMMENDED PICKET SHIP AND TEXAS TOWER RADARS*						
Function	Frequency (Mcps)	Peak Power (Mw)	Rep. Rate (pps)	Pulse Length (μsec)	Antenna Size vert. horiz. (ft)	Max. Range (n.mi.)
Picket ship air search	600 ±7%	10	300	7	25 × 45	620
Picket ship stacked-beam search and height-finding	1250 ±5%	10	300	7	25 × 45	370
Picket ship nodding-beam height-finding	5650 ±5%	2	300	2	20 × 10	320
Texas Tower air search		same as ground radar, Appendix 4-A				
*All rotation rates are 6 rpm						

TABLE 4B-II				
RADARS ENCOUNTERED BY THE ENEMY				
Function	Wavelength (cm)	Bandwidth (Mcps)	Peak Power (Mw)	Pulselength (μsec)
AEW search	10	20%	2	2
AEW search	70	30	2	6
AEW search	70	30	4	2
AEW height	3.2	60	0.45	1.8
AEW height	5.4	20	2	2
AEW search and height	10	60	5	1
Ship search	50	20	10	7
Ship height	5.4	20	2	2
Ship search and height	25	20	10	7

certain shore radars, including the height finders — and that he will endeavor to have equal self-screening range against all search radars. On this basis, and using the same assumptions as outlined for ground radars in Appendix 4-A, the same self-screening range of about 34 miles will be obtained, because the enemy will have to prepare to jam the Texas Towers and shore-based radars.

If the enemy were to choose a sea approach to the North American continent, and were to equip his bombers only for jamming of picket ship and AEW radars, he would have to operate in the bands shown in Table 4B-II. The optimum self-screening range for the ensemble of radars listed is 7 miles, calculated as outlined in Appendix 4-A.

Either of the picket-ship radars, alone, would be capable of fulfilling the search-radar requirement for intercept control. The 600-Mcps radar azimuth beamwidth is 2.7°, and the vertical aperture will allow solid coverage to 100,000 feet with very little effect from weather. The 1200-Mcps radar has an azimuth beamwidth of 1.4°, and the stacked-beam search coverage will also extend to 100,000 feet. Using 7 lobes, this antenna size will allow coverage on targets up to 20° elevation, leaving only a very small hole, overhead, in which aircraft cannot be detected. With suitable antenna design and with suitable receiving components, height can be determined with an accuracy of about ± 3000 feet out to 200 miles on all targets above the horizon, which is well within the limits outlined in Chap. 4 for AEW requirements. The 5650-Mcps nodding-beam height finder has a 0.6° vertical beamwidth, and should also find height to an accuracy of ± 3000 feet on all targets above the horizon within 320 n. mi. of the ship. In addition, it can be made to have a pulse-Doppler listening ability, using an alternative higher pulse rate, as an aid in analysis of raid size. The azimuth beamwidth of this radar is 1.3°, which results in a certain immunity to weather effects (such as echoes from storm clouds), although this frequency is more vulnerable to such effects than either of the other frequencies. This frequency is the only one that is common to both the AEW aircraft and picket ships, being used for height in both cases. However, if the enemy were to use jamming on this frequency and not on the search-radar frequency, the close association with the search radar would still allow height to be determined. The technique would be to display a cursor from the search set on the height indicator at the range of the target. The operator would turn down the height receiver gain until the enemy jamming appeared as a single line at the elevation angle of the target. The intersection of this line with the range cursor would be target height. The stacked-beam set can be used the same way.

Antenna stabilization for the two search radars is required on picket ships. Probably the most convenient way to mount the two search radars is by combining the antennas

on one stable platform with the reflectors back-to-back. Stabilization over roll angles of ± 15° and pitch angles of ± 10° undoubtedly is sufficient. The combination of low roll angles, low roll rates, and low-level mounting of the antenna should result in modest requirements on the stable platform and make it possible to avoid excessive antenna weight. Another suggestion worth careful consideration is the use on picket ships of a hemispherical inflated radome such as is used for arctic radars. In arctic service, these radomes withstand high winds and severe icing conditions. The effects of salt air and stack gases will need investigation, but tremendous savings in antenna design will result if a suitable radome material can be found. If the radome takes the wind load the antenna stiffness could be reduced, as could the weight and power of the stabilization system.

Plans for Texas Towers do not as yet include installation of antennas as large as those listed for ground radars. The size of the tower is large enough, however, that horizontal antenna apertures of the largest recommended size (240 feet) could be mounted, at least using fixed antennas with beam scanning by phasing. It is not impossible that the very large rotating antennas which were recommended in Chap. 4 could be used on Texas Towers.

J.L. Schultz

APPENDIX 4-C
RADARS FOR MERCHANT SHIPPING

The use of merchant ships in the Atlantic and Pacific oceans to provide a general surveillance capability has been proposed as part of the Lamp Light defense system. The choice of a radar for outfitting such vessels will be influenced by several factors:

Range and coverage of radar,
Reliability of operation,
Necessity for continuous attendance,
Service time required,
Cost of installation, operation and maintenance.

The number of vessels that can be outfitted in this way will depend on the size, complexity, and operating requirements of the radar; thus the effectiveness of the over-all system may decrease beyond a certain point as the range performance of the radar increases. It becomes desirable, therefore, to investigate the interrelationships of some of the above factors before arriving at a specific proposal for a radar.

Elementary considerations show that the expected number of reports k, on a target traversing a path through an area covered with randomly situated radars, is given by $k = 2NRL$, where R is the radar detection range, N the number of radars per unit area, and L the length of path through the area. It is seen that the number of radars required to achieve a specific result is inversely proportional to the range of the radar.

Figure 4C-1 shows a map of the North Atlantic, the dotted area showing roughly the portion over which there is quite uniform distribution of ships. There are very few ships above the 50th parallel in the Western Atlantic. (See also Chap.13 and App.13-E.)

The dashed line shows a possible route of attack that avoids the contiguous cover near shore, and is over densely populated water for a minimum distance. This distance, from the 50th parallel to 100 miles offshore, is 1500 miles.

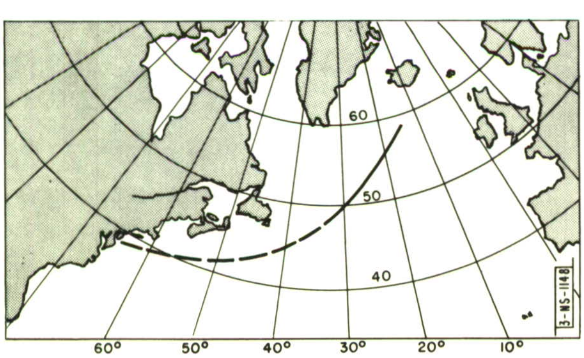

Fig.4C-1. Selected route.

In order to reduce the random chance of an undetected crossing, k (the expected number of reports) should be larger than one. The probability of obtaining x reports when k is the average is given by

$$P(x) = \frac{(k)^x e^{-k}}{x!}$$

If k is chosen as 4, the chance of obtaining at least one report is 98%, at least two reports is 91%, at least 3 is 76%, and four or more is 67%.

Using the values L = 1500 miles, k = 4 in the formula for k, it is found that N = 1/750 R.

If a radar with a 20-mile range is chosen, N becomes 1/15,000, i.e., one ship for every 15,000 square miles. The average spacing is $\sqrt{15,000} = 120$ miles. If the density of these ships is assumed uniform over a belt roughly lying between the 30th and 50th parallels in the North Atlantic, the total area is about 3×10^6 square miles, so that 200 radar-equipped ships, randomly dispersed throughout this area, would be required.

Actually, the nonuniform distribution of ships, with the marked increase in density near the terminals of the routes, and the fact that much area would be covered that is not of interest for this purpose, makes this first approximation a rather crude one. However, two facts are rather striking: first, the number of radars required is only inversely proportional to the range (not to the range squared); and second, the average spacing between equipped ships can be many times the radar range.

A more detailed approach can be made by choosing first the type of vessel according to suitability and normal route, determining the density of these along the route where expected crossings will take place, and then plotting cumulative-probability-of-detection curves for various numbers of ships equipped. Because ships not ordinarily traversing the sensitive area (e.g., Gulf of Mexico tankers) can be eliminated, the total area used in the calculation may be reduced somewhat.

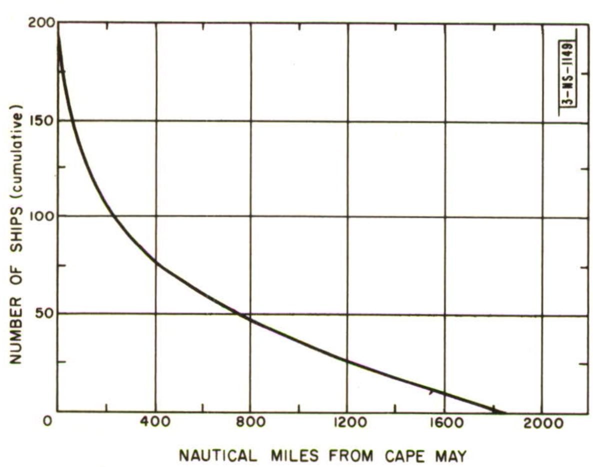

Fig.4C-2. Cumulative number of ships over 1600 tons encountered over 200-mile-wide path along route of Fig.4C-1.

A map showing the distribution of ships in the North Atlantic as of 1 May 1952 was used. An anticipated target route was drawn in on this map as in Fig. 4C-1, a swath 200 miles wide described about it, and the density of ships within the swath determined. The ships counted were all those over 1600 tons except tankers. Figure 4C-2 gives the cumulative number of ships encountered in this swath as a function of distance along the route.

Given the radar range and percentage of these ships equipped, the expected number of contacts can be obtained readily from

this curve. The scale given on the curve corresponds to using all ships and a 100-mile radar; it is to be modified in direct proportion to the radar range and the fraction equipped.

Figure 4C-3 shows the cumulative probability of obtaining at least one radar intersection as a function of distance along the route from the shore line. It will be seen that equipping all ships with 30-mile radars is excessive from this standpoint – one-third the number of ships or one-third the radar range would give almost as good results. However, use of a 10-mile radar with only 20% of the ships equipped does not rise to 90% probability until 200 miles off the coast – an uncomfortably short distance.

Since some knowledge of the target position as a function of time is highly desirable, a better question to ask concerns the probability of getting several reports. Figure 4C-4 shows the cumulative probability of obtaining at least three reports on a target by the time it has travelled to the indicated distance.

Examination of these curves indicates that very satisfactory results can be obtained if 60% of these ships are equipped with a 10-mile radar or, what is equivalent, 30% of the ships with a 20-mile radar. In the former case, a density of one radar per 5000 square miles is required; in the latter case, one radar per 10,000 square miles will suffice.

While good range performance is always desirable, it is apparent that it is not necessary to go to extremes, since a quite modest range will do the job. Indeed, there are some virtues to using short range and large numbers, chiefly in that the statistical fluctuations in the effectiveness of the system are reduced, and fewer reports are required from any individual ship.

In view of the service this radar must perform and the nature of the vessels on which it is to be installed, it was felt that an automatic alarm-ringing radar that does not require an operator would be most desirable.

Table 4C-I is a listing of some possible radars of this type, together with their characteristics.

The X-3 radars are experimental modifications of the TPS-1D, fitted with automatic alarm-ringing circuits and various antennas.

The Chipmunk II is a lightweight portable automatic alarm-ringing radar developed at Lincoln Laboratory for the Ground Observer Corps; the Super Chipmunk is an enlarged version suggested here for application to merchant ships. The rather conservative ranges reported are due in part to the small target size assumed, and in part to the

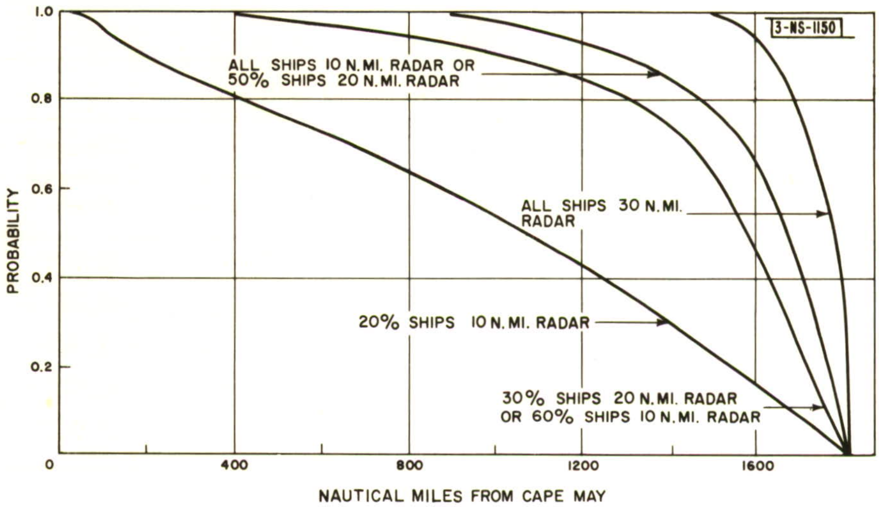

Fig.4C-3. Cumulative probability of at least one report along chosen route.

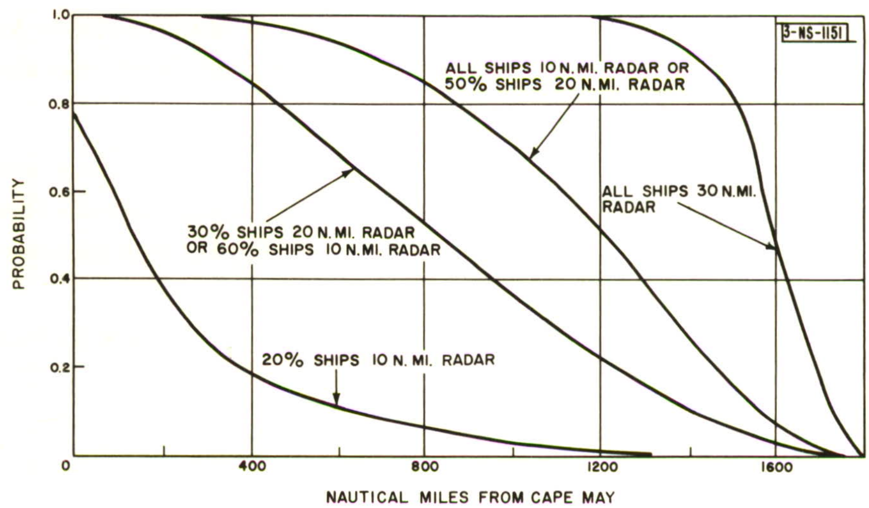

Fig.4C-4. Cumulative probability of three or more reports.

TABLE 4C-1						
RADARS FOR MERCHANT SHIPS						
Type	Peak Power (kw)	Avg. Power (watts)	Frequency (Mcps)	Antenna Size (feet)	Altitude Coverage (feet)	Range on 2-m^2 Target (n.mi.)
X-3	166	500	1200	15 × 4	20,000	50
X-3	166	500	1200	15 × 2	45,000	30
X-3	166	500	1200	25 × 14	45,000	70
Chipmunk II	0.05	2	118	5 (Yagi)	60,000	8
Super Chipmunk	1.5	90	425	7 × 7	45,000	20

automatic alarm feature, which requires large signal-to-noise ratios to avoid unduly high false-alarm rates.

Of the various possibilities, a radar similar to that described in Appendix 4-D is recommended primarily from the standpoint of simplicity, reliability, and freedom from the necessity for frequent maintenance and adjustment. The antenna is small enough to permit easy installation on a wide variety of craft with little interference with other services. No additional personnel will be needed and no watch need be kept; maintenance is expected to be required so infrequently that an "in port" check every few months will suffice.

While more elaborate radars might well be installed on those vessels with sufficient personnel to operate and maintain them, it appears the maximum effectiveness of a general surveillance system will be attained by providing a large number of ships with small and simple automatic radars.

J.W. Coltman

APPENDIX 4-D

A DESIGN FOR A 20-MILE AUTOMATIC-ALERTING RADAR

INTRODUCTION

A laboratory model of a simple low-power automatic alarm radar capable of detecting B-47 aircraft at a range of 8 miles is presently being evaluated at Lincoln Laboratory. (See also Chap. 13 and App. 13-E.)

This Appendix outlines one set of parameters for a similar type of radar that would be capable of detecting a 2-m^2 target at a range of 20 nautical miles at altitudes up to 50,000 ft.

The use of existing standard radar equipment to achieve the desired coverage would result in a complex and expensive installation that would require skilled field personnel for maintenance. By sacrificing data rate and resolution, it appears feasible to obtain the required coverage with a minimum of equipment complexity.

PERFORMANCE REQUIREMENTS

The radar should be capable of detecting a 2-m^2 target at ranges of 20 nautical miles and at all altitudes up to 50, 000 ft. The coverage desired is plotted in Fig. 4D-1. Since the radar would be used primarily in areas having a low traffic density, it should be automatic in operation, i.e., sound an alarm whenever an aircraft enters its field of view. It need not be portable since it would be designed primarily for installation within buildings and/or on shipboard.

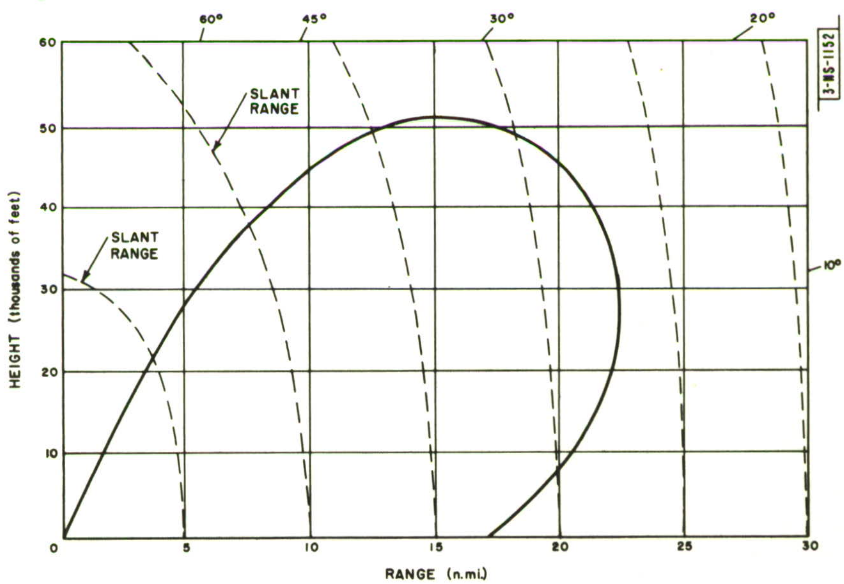

Fig. 4D-1. 425-Mcps low-power automatic-alerting radar. Calculated coverage on a 2-m^2 target.

This radar equipment would be designed for use by non-technical personnel. The general complexity and total number of adjustments should be comparable to that in a standard TV receiver. The reliability of the over-all radar should be sufficiently high to provide for continuous operation for periods of at least 3 months without maintenance.

FACTORS INFLUENCING EQUIPMENT DESIGN

Reliability and Simplicity

Since it is intended that this radar be utilized by non-technical personnel, it must be relatively foolproof and have only 1 or 2 adjustments available to the operator.

MTI Capability

It will be necessary to operate automatic-alarm circuits in regions of heavy ground clutter; therefore the radar should utilize coherent Doppler principles for separating fixed from moving targets. A pulsed radar system should be employed since it will then be feasible to separate signals at one range from clutter at other ranges, thereby obtaining increased subclutter visibility.

Automatic-Alarm Capability

A number of independent automatic-alarm warning bands should be provided so that automatic detection can properly constitute the primary mode of operation. Three or four range rings, each matched to the pulsewidth, should provide for adequate detection coverage. The warning bands would be staggered in range. Typical gate positions would be 8, 12, 16, and 20 miles.

Resolution – Data Rate

A compromise must be made between range resolution, antenna rotation speed, and pulselength, in order to optimize the performance of the alarm system. Since these radars would be used primarily in early-warning functions where the data transmission time is at least 2 to 5 minutes, resolution greater than 15° in azimuth and 2 miles in range does not seem necessary.

Choice of Frequency Band

There does not appear to be a single optimum frequency band for this equipment. Low frequencies, on the order of 100 Mcps, result in simple transmitting and receiving components, but it is difficult to shape the antenna beam effectively without the use of large antenna apertures. Impulse noise from automobile ignition systems may restrict the usefulness of 100- to 300-Mcps equipment in urban areas. On the other hand,

higher frequencies, of the order of 600 Mcps, make it possible to control the antenna radiation pattern, but the complexity of the RF components in the transmitter-receiver is increased. The design calculations discussed later in this Appendix have been based on a frequency of 425 Mcps.

Size and Power Consumption

Since this equipment will be installed within existing buildings or on shipboard, size is of only secondary importance, and reliability should not be compromised for compactness. It is believed that the basic radar and alarm circuits, exclusive of antenna, can be packaged into a box approximately $2 \times 2 \times 2\text{-}1/2$ feet. The primary power consumption, to obtain the indicated performance, is expected to be of the order of 500 watts. This power can be substantially reduced through the use of transistors and by design refinement.

Antenna

In order to achieve the range and altitude coverage indicated in Fig. 4D-1 with a relatively low-powered simple transmitter, the largest acceptable antenna aperture is desirable. A 14×5 foot aperture has been selected for test calculations. Although this aperture may appear to be relatively large, the reflector can be made of 3×3 inch mesh and be supported by a lightweight tubular steel framework.

SUGGESTED PARAMETERS FOR 20-MILE RADAR

Based upon experience with Chipmunk II, and taking into account the factors previously discussed, the following parameters of Table 4D-1 are suggested for the 20-mile radar.

The display would be an array of lights that would indicate the range and approximate azimuth of targets. A small A-scope and a loudspeaker would supply additional data about the character of the aircraft echo. The specific field application will determine, to a large extent, the data-presentation requirements.

PERFORMANCE CALCULATION

The performance of this radar is computed using the method outlined in Ref.1,* Lincoln Laboratory Technical Report No. 24, 4 August 1953, pp. 15-22.

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*Reference 1.

TABLE 4D-1	
PARAMETERS FOR A 20-MILE RADAR	
Frequency (Mcps)	425
Peak Power (kw)	2
Pulsewidth (μsec)	20
PRF (pps)	2000
Average power (watts)	80
Antenna	
Horizontal beamwidth θ_H (deg)	12
Vertical beamwidth θ_V (deg)	32
Gain (db)	18
Aperture (ft)	14 x 5
Receiver	
Noise figure (db)	7
IF bandwidth (kcps)	50
Antenna rotation rate (rpm)	4
Alarm rings	4

Range

The range of the single pulse system is given by:

$$R = 10.1 \left[\frac{P G^2 \lambda^2 \sigma}{(NF)\,(B)\,(S/N)} \right]^{1/4} \text{ n. mi.,} \tag{1}$$

where

P = peak power in watts,
G = antenna gain (one-way power),
λ = wavelength in meters,
σ = echoing area,
NF = receiver noise figure,
B = receiver bandwidth (cps),
t = transmitted pulsewidth,
S/N = signal-to-noise ratio required to operate the display or alarm device,
R = range in nautical miles.

For the system under consideration:

P = 2000 watts,
G = 63 (18 db),
λ = 70 meters,
NF = 7 db (5),
t = 20 μsec,
B = 50,000 cps.

Substituting these numbers in Eq. (1), we find

$$R = 20.1\left[\frac{\sigma}{S/N}\right]^{1/4} \text{ n. mi.} \tag{2}$$

Determination of S/N Requirement at Alarm Device

The number of discrete azimuthal positions in the system will be:

$$\text{Azimuthal positions} = \frac{360}{\theta_H} = \frac{360}{12} = 30 \quad .$$

Since there will be 4 gates, there will be $4 \times 40 = 120$ decisions per revolution. At 4 rpm, there will be 480 decisions per minute. In a one-month time interval, there will be approximately 2×10^7 decisions.

Relating the probability of detection to signal-to-noise ratio (Ref. 1) it is possible to determine the required S/N for any acceptable false-alarm rate. If we assume that the false-alarm rate should be 1 per month (once per 2×10^7 decisions), then it can be shown that, for a 90% probability of detection, a S/N of 13.6 db (23) will be required at the decision-making device.

Improvement in Range Due to Integration

The number of pulses on a target is given by the following equation.

$$\text{Number of pulses on target } (n) = \frac{\text{prf} \times \text{sec/rotation}}{\text{azimuthal positions/rotation}}$$

$$= \frac{2000 \times 15}{30} = 1000 \quad .$$

If the output of the integrator is proportional to $(n)^{0.7}$ (Ref. 1, Figs. II-2 and II-3), then the integration gain is 125.

In computing the signal-to-noise improvement with integration, we assumed that 1000 uniform pulses of energy were being integrated. It is necessary to allow for the shape of the antenna beam and for the complex nature of the target echo. An allowance of 2 db for each of these factors is necessary.

Then the required signal-to-noise with integration is equal to the signal-to-noise without integration times the power loss due to antenna and target fluctuation divided by the integration gain, or

$$\frac{23 \times 2.5}{125} = 0.46 \quad .$$

Substituting this value of S/N into Eq. (2), we find the range with the automatic-alarm system to be

$$R_{max} = 24.3\, [\sigma]^{1/4} \quad .$$

Allowing an additional 4 db for system degradation,

$$R_{max} = 19.3\, [\sigma]^{1/4} \quad .$$

For a one square meter target,

$$R = 19.3 \text{ n. mi.}$$

For a 2 square meter target,

$$R = 23 \text{ n. mi.}$$

For a 40 square meter target (B-29),

$$R = 48.5 \text{ mi.}$$

The above calculations indicate the performance that should be obtained over nonreflecting terrain. When the equipment is installed over smooth terrain or over water, the ranges will be substantially increased.

There are many possible sets of parameters that could provide equivalent performance. In situations where it is feasible to employ a larger antenna system, equipment complexity can be reduced.

H.G. Weiss
Lincoln Laboratory

REFERENCE

1. H.G. Weiss, et al., "Automatic Alerting Radar for Project Counter Change," Technical Report No.24, Lincoln Laboratory, M.I.T. (4 August 1953).

CHAPTER 5

FLUTTAR DETECTION SYSTEMS

CHAPTER 5

FLUTTAR DETECTION SYSTEMS

PRINCIPLES

Fluttar detection differs from radar in that the transmitter and receiver are separated. A moving target crossing the line between them modulates a fixed-beam CW transmission. Only moving targets that produce a Doppler beat between the signal scattered forward from the aircraft and the directly propagated reference signal are detected. A typical Fluttar system uses a fence of alternate transmitters and receivers spaced 50 to 60 miles apart, radiating 50 watts CW at 500 Mcps, with fixed antennas beamed along the line.

As now used, an unmodulated reference is continuously transmitted over the surface of the earth to the receiver. The terminals are spaced to be below the horizon to insure that the directly transmitted reference is not too strong. The geometry of the system is displayed in Fig. 5-1.

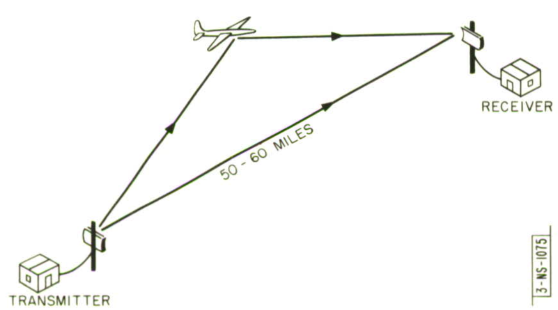


Fig. 5-1. Arrangement of Flutter Stations in a single line.

The frequency of the energy reflected by the target to the receiver is slightly shifted because of target motion. On detection, interference with the unshifted reference produces a typical Doppler signal. Alarm is obtained from a series of narrow-band audio filters that are excited in turn as the target crosses the line and the Doppler frequency changes. In addition, and most important, the waveform of the Doppler signal is continuously recorded to allow audio and visual examination, playback and analysis.

SIGNAL ENHANCEMENT AND TARGET FLUTTAR-PRINTING

The most important advantage of Fluttar is the large enhancement of target signal scattered forward to the receiver as compared with radar backscatter.

A careful series of measurements made by J. R. Whitehead for the Canadian Defence Research Board in the Summer of 1954 shows a consistent enhancement of 25 to 45 db on aircraft targets, with the largest values corresponding to heights below 5000 feet. In cones directly over the terminals, a fluctuating enhancement of 0 to 26 db is found, while at the center of the path the enhancement tends to be maximum. Earlier measurements made by the Air Force Cambridge Research Center had indicated an enhancement of 15 to 25 db.

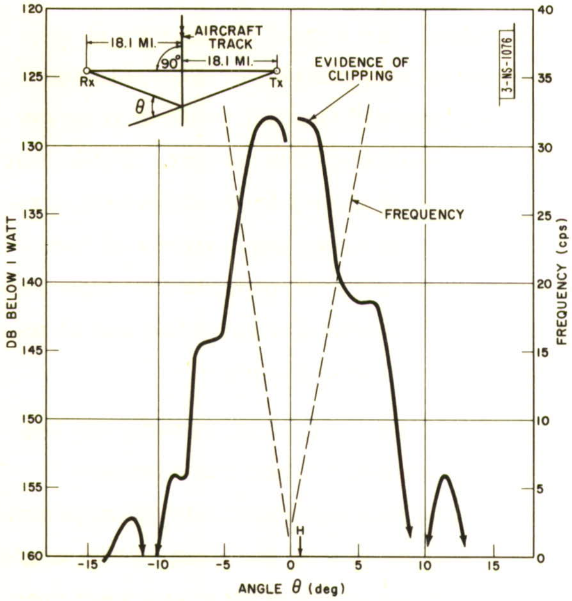


Fig.5-2. Diffraction pattern for CF-100 aircraft. Altitude: 20,000 ft; ground speed: 500 mph; angle to beam: 90°; position: midway along beam.

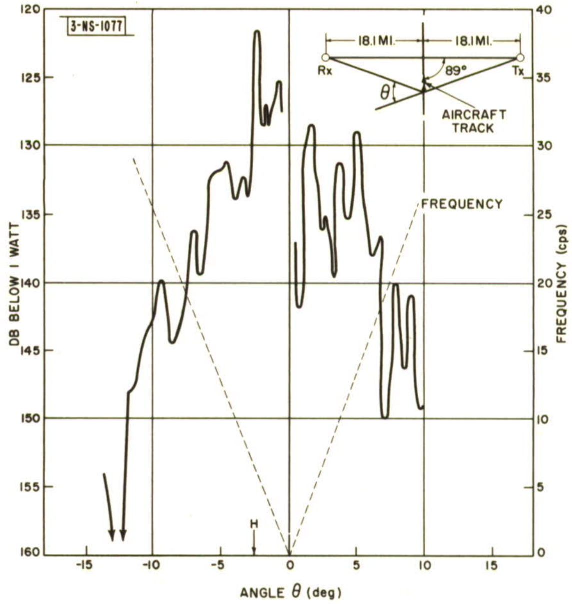


Fig.5-3. Diffraction pattern for B-36 aircraft. Altitude 20,000 ft; ground speed: 201 mph; angle to beam: 89°; position: midway along beam.

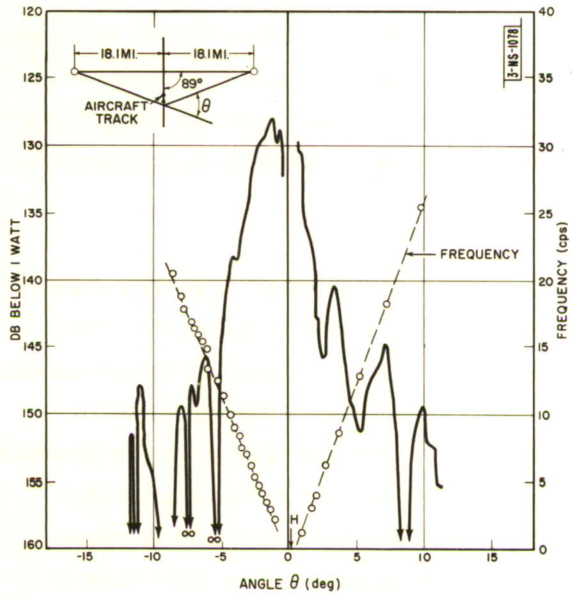


Fig.5-4. Diffraction pattern for Lancaster aircraft. Altitude: 20,000 ft; ground speed: 164 mph; angle to beam: 89°; position: midway along beam.

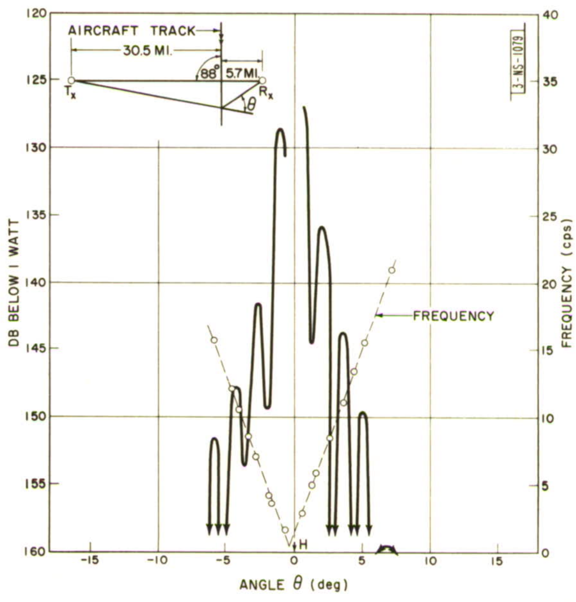


Fig.5-5. Diffraction pattern for Lancaster aircraft. Altitude: 500 ft; ground speed: 200 mph; angle to beam: 88°; position: 5.7 mi. from receiver.

The maximum enhancement is closely confined to the vertical plane between transmitter and receiver. As the aircraft crosses this plane, the signal fluctuates in a complicated and characteristic manner. The resulting diffraction pattern may be said to Fluttarprint the target. Different patterns are obtained from different aircraft and from close formations of two or more aircraft. Provision for tape recording and playback allows for aural as well as visual identification.

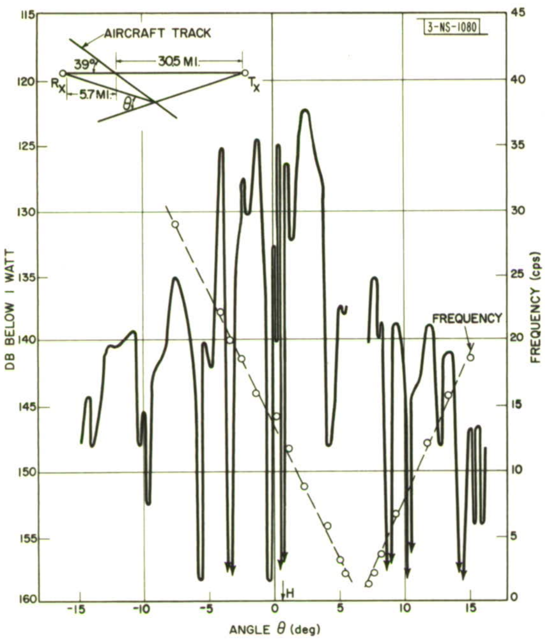


Fig. 5-6. Diffraction pattern for B-36 aircraft. Altitude: 20,000 ft; ground speed: 301 mph; angle to beam: 39°; position: 5.7 mi. from receiver.

The enhancement falls off rapidly as the target moves away from the system baseline and has substantially disappeared at the distance where the sum of the angles subtended from transmitter and receiver is between 2° and 15°, depending upon such factors as aircraft length, angle of crossing and position of crossing.

Figures 5-2 to 5-6 are examples of diffraction patterns for different aircraft, at different heights, and crossing the baseline at different angles and positions. This ability to Fluttarprint the target provides an important aid to recognition which might profitably be used as a complement to radio information.

SYSTEM SENSITIVITY AND LOW COVER

Above the horizon, radar sensitivity falls off as the fourth power of the distance of the target from the station. In Fluttar, however, because the transmitter and receiver are separated, the situation is more complicated. Considering range alone, the sensitivity varies inversely as the product of the squares of the distances to the two terminals. Taking into account also the variation of cross section with target position, it is possible with suitable antenna design to obtain at a given height in the free-space region a nearly constant target sensitivity over the whole Fluttar link. The figures in Appendix 5-A illustrate this fact.

This nearly constant sensitivity as a function of range makes Fluttar less susceptible to jamming than radar. Decoys such as corner reflectors designed to deceive radar will not be seen on Fluttar. Forward-scattering decoys will be developed; however, a combination of Fluttar and radar stations, because of their different characteristics, will make jamming and decoy techniques more difficult for the enemy.

Below the horizon, as discussed in Appendix 5-A, additional attenuation occurs in the diffraction region, and beyond this, in the scatter region. Consequently, the sensitivity on long links at low heights will vary considerably from transmitter to receiver. The regions of minimum sensitivity are near the quarter-points, as may be seen from the figures in Appendix 5-A. This wide variation in sensitivity at low heights on long paths may result in small targets such as birds, in sensitive regions of the link, that produce as large signals as aircraft in other parts of the link.

Nevertheless, Fluttar has great advantages over radar for low cover, since the latter has negligible sensitivity below the horizon. At a link spacing of 60 miles, Fluttar provides complete cover from 200 to 60,000 feet from transmitter to receiver, with 50 watts power.

FALSE ALARMS AND NOISE

In a detection system, it is just as important not to have false alarms as to get positive warning on real targets. Birds in the sensitive regions of a long Fluttar link may produce large signals.

Two approaches to this problem have been developed. In one, the system accepts all signals – from small slow-moving objects as well as from large fast targets. Discrimination is then obtained on the basis of amplitude and characteristic diffraction pattern as already discussed. In the other approach, the system is designed to reject signals from targets moving below a given velocity. This velocity rejection, however, requires that the system be made sensitive only to targets in a region offset from the median plane between transmitter and receiver. The system therefore sacrifices the large forward-scatter gain obtainable in the median plane.

Experiments are being undertaken in Canada to measure the forward-scatter cross section of birds in different parts of a Fluttar link during the 1955 spring migration. However, it is already clear that, with proper system design, birds can be discriminated from aircraft on Fluttar links of 50 to 60 miles in length.

Another possible source of false alarm is noise. It has been found that noise modulation on the carrier increases rapidly below 10 cps. This noise is apparently due to small variations in propagation of the reference signal.

Although measurements of this scintillation noise are as yet very inadequate, its approximate level is shown in Fig. 5-7. The importance of this scintillation lies in the fact that it becomes large at low frequencies. On the other hand, forward-scatter

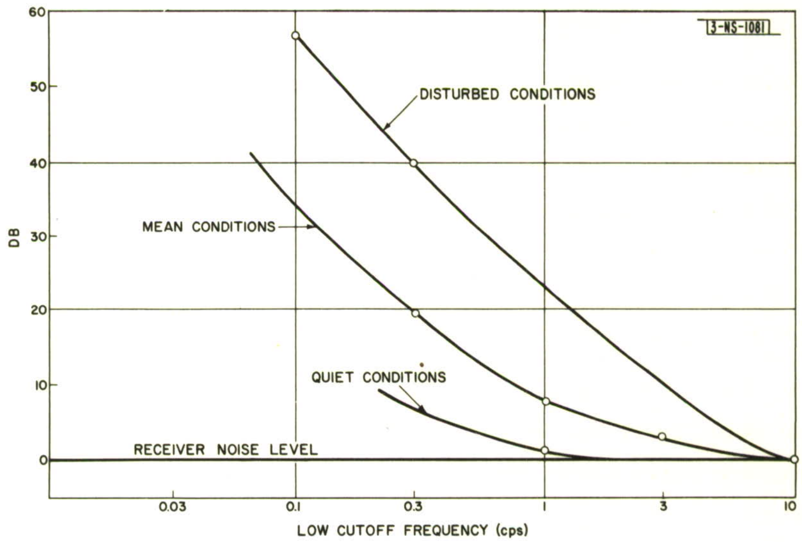


Fig.5-7. Approximate rms scintillation noise in Doppler band with high cutoff at 50 cps.

signal enhancement becomes large only very near to the median plane through the Fluttar link, and it is here that Doppler frequencies normally pass through zero. As a consequence, it has been found that scintillation noise limits target-signal detection below about one cps. Quantitative measurements of scintillation noise are now under way.

THE REFERENCE SIGNAL

In present equipment, the reference signal at the receiver must be about 30 db above the minimum target alarm level of approximately −170 dbw.

Experiments indicate that the mean reference signal is predictable on links up to 70 miles within approximately 3 db by the methods of Bullington. Fading well below the horizon is found to be within a total range of 40 db for 99 per cent of the time, divided into 15 db of upward fading and 25 db of downward fading.

Large downward fades may make long links inoperative because of the absense of a suitable reference. Large upward fades may so increase scintillation noise that target

detection is impossible. Consequently, low cover on long links may be limited by the requirement of a stable reference.

Proposals designed to reduce this limitation on long links are discussed in Appendices 5-B and 5-C. The most direct proposal is to use stable oscillators at each end and to suppress the transmitted reference. A second is to send the signal back and forth between terminals via the target. Both of these proposals require suppression of the signal propagated over the direct path. Such suppression probably requires offset beams, with consequent sacrifice of high forward-scatter gain. A third proposal involves pulsing the transmitter and separating the reference signal from the target signal by the difference in the transit time.

None of these ideas has been sufficiently examined, but further investigation and test are very desirable.

PRESENT SYSTEMS DESIGN

At present, two Fluttar systems are being engineered. The Canadian system is being developed for the Mid-Canada Line, and the Lincoln Laboratory system for low cover in the DEW line. The two approaches are the result of different assumptions made about the effects of signals from birds.

The Canadian system is designed to accept all Doppler frequencies above one cps that have the expected signal amplitudes from aircraft within the required cover (200 to 60,000 feet) and to discriminate against bird echoes, essentially on the basis of amplitude and characteristic diffraction pattern. The minimum recordable signal will be below the minimum anticipated aircraft signal within the coverage. Consequently, as an important auxiliary to detection, an operator will examine the characteristic waveform output from the Doppler detector.

The sense of crossing, from north to south or south to north, is determined by having two lines of stations separated by 3/4 to 8 miles. This double line of detection stations also increases reliability and discrimination against false alarms.

In the Lincoln system, the basic assumption is that bird signals must be eliminated at the outset. This is accomplished by rejecting all Doppler frequencies below about 45 cps. By this means, provided that antennas are designed to reject targets behind the terminals, any target flying less than 60 mph is eliminated. This approach is the consequence of experimental evidence on a Lincoln 50-mile link that birds of the size of sea gulls can be detected. Measurements made at Air Force Cambridge Research Center indicate that an average duck has an effective cross section of the order of

$0.02\ m^2$. For a single bird, the ratio of aircraft to bird cross section is about 30 db. This ratio may be appreciably reduced by a flock in flight formation.

In order that aircraft targets may be detected from Doppler signals above 45 cps, the Lincoln system requires offset antennas. The Doppler frequency produced by a moving target is proportional to the rate of change of the sum of the distances to the two terminals. In general, this passes through zero near the system baseline. Consequently, in the Lincoln system the antennas must illuminate a region offset from the baseline where aircraft Doppler frequencies will be above 45 cps.

Although this offset system sacrifices forward-scatter gain, it has the advantage that the sense of crossing is determined from a single line of stations. Thus, the order in which Doppler frequencies are excited determines whether the target is approaching from the south or the north.

NEW FLUTTAR SYSTEMS

A simple Fluttar fence gives warning of penetration. It does not locate the target, except within the length of a link, which may be 50 miles. However, one Fluttar link determines accurately the time at which a line is crossed. Dr. Bode of Bell Telephone Laboratories has pointed out that if a Fluttar net is set up, which would naturally be irregular in form, but which for simplicity may be thought of as consisting of rectangular cells, then if a target crosses four links, four such times are accurately determined. Provided that the target has not changed course in the interval, these four times are sufficient to determine accurately the aircraft position and velocity. Not always

In addition, Dr. Skolnik of Lincoln Laboratory has pointed out that, in principle, one Doppler link is sufficient to determine the track, speed and height of a target. The Doppler frequency excited by a target is proportional to the rate at which the ellipsoidal surfaces of integral wave number between terminals are cut. If the times at which five Doppler frequencies are excited can be recorded with sufficient accuracy, it is a matter of simple geometry to show that the track, speed and height of the target can be determined.

The use of a net of Fluttar links, with each link giving a measure of track, speed and height at a given point and with successive links establishing, confirming and extending the information, would appear to have considerable promise. Processing and correlating the data would be performed by computers at regional centers.

Insufficient study has been given to these proposals, and it is strongly recommended that they be thoroughly investigated through further research and development.

CHAPTER 5 RECOMMENDATIONS

1. *We recommend further investigation and development of detection systems such as Fluttar using the principle of forward scatter.*

2. *We recommend the use of Fluttar to complement radar information for early information lines, particularly where low cover at long range is a requirement.*

3. *We recommend further investigation of the use of forward-scatter target-diffraction patterns (Fluttarprints) to distinguish between different aircraft, between single and multiple targets, and between aircraft, birds and other sources of false alarms.*

4. *We recommend investigations leading to the elimination of the requirement in Fluttar systems for transmission of a reference signal over a separate propagation path, either by provision of a stable reference at the receiver or by return of the target signal via the target.*

5. *We strongly recommend research on, and development of, the use of Fluttar nets to obtain target position, course and speed, as well as height.*

APPENDICES TO CHAPTER 5

APPENDIX 5-A

THE FEASIBILITY OF LONG FLUTTAR LINKS

Introduction

500 MEGACYCLES

The optimum length of a double-station Doppler detection link has been considered for some time as 35 miles for 50 watts of transmitter power. The purpose of this appendix is to predict the approximate coverage of links much longer than 35 miles. The coverage depends upon transmitted power, receiver sensitivity, antenna performance, tower height, and estimated aircraft cross section.

In order to reduce the number of different possibilities, certain assumptions have been made and are described below.

Assumptions

Propagation:– All the links considered here are over smooth earth. Normal conditions are taken to correspond to an effective earth's radius of 4/3 R, where R is the true radius of the earth.

The computation of signals diffracted beyond the horizon follows the methods of Bullington (Proc. I. R. E., October 1947, p. 1122). A frequency of 500 Mcps has been assumed throughout. The computation of the magnitude of tropospheric-scatter signals is on the basis of a loss of 24 db below free space at 30 miles and –18 db per doubling distance beyond that range, in addition to the free-space loss (–6 db). This appears to be the best information available at present. It is taken from Bullington's summary of his own experimental results and those of other workers.

It is assumed that the tropospheric-scatter loss far beyond the horizon is independent of tower height. Curves of field strength at a given location as a function of height therefore show a sharp transition from the free-space value through the diffraction region to the constant value corresponding to tropospheric scatter as the height is reduced below the horizon. Figures 5A-1 and 5A-2 show sets of curves computed for 300- and 5000-foot site locations for a series of different ranges. The curves give the field strength from a 10-kw transmitter in dbw/m^2 as a function of height. These curves are used as a basis of the echo-strength computations that follow.

The shape of the transmission between free space and tropospheric propagation, i.e., the diffraction region in Figs. 5A-1 and 5A-2 can only be approximated, and the values shown have meaning only as approximate average figures. These values will fluctuate with fading conditions somewhere between the two extremes corresponding to free-space and tropospheric-scatter propagation.

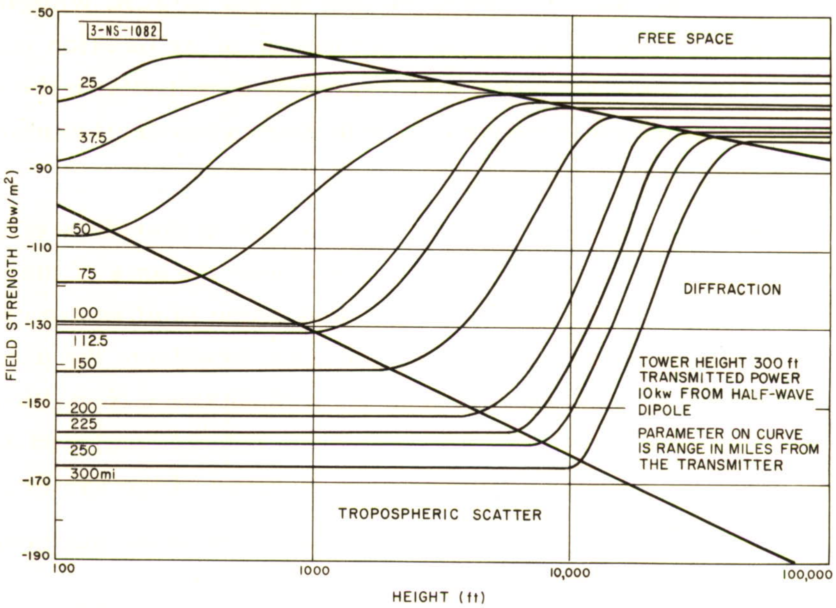


Fig. 5A-1. Field strength as a function of height (300-foot tower).

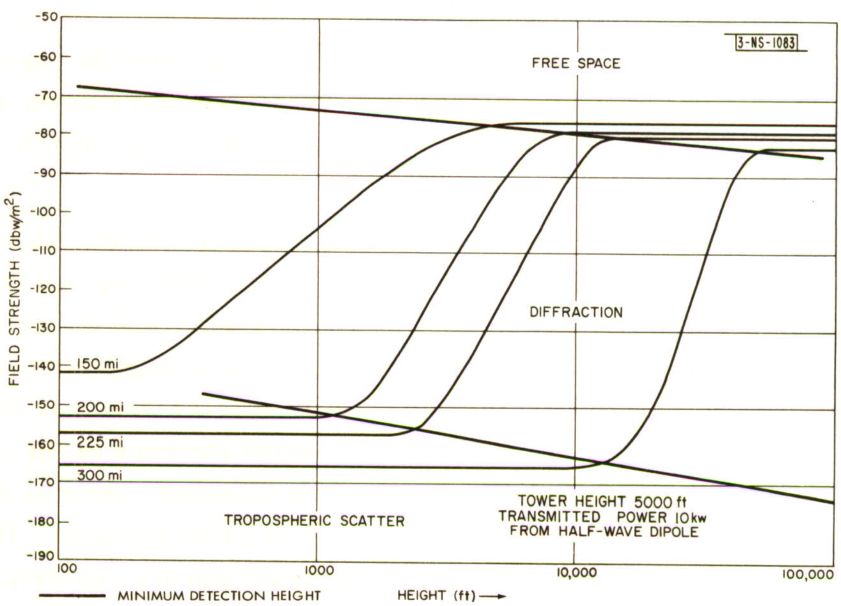


Fig. 5A-2. Field strength as a function of height (5000-foot tower).

<u>Aircraft Cross Section</u>:– The results of recent experiments by J. R. Whitehead show that the effective cross section of an aircraft is a function of its location in a double-station Doppler link. They also indicate a high degree of directivity in the signal diffracted from the aircraft which increases the effective cross section markedly along the line of the illuminating beam extended.

The main beam of the diffracted signal is 1° to 2° wide and is therefore effective only when a low Doppler frequency is being produced, i.e., near the axis of the system. The figures that follow have been computed on the peak value of effective cross section corresponding to illumination of the receiver by the main lobe from the aircraft. Figures for the rate at which the cross section falls off with distance from the axis are not yet available, but the salient feature here is that the echoes computed are the largest that are obtainable by taking advantage of all the features of the system.

The following values of the effective cross sections taken are those measured on a Lancaster aircraft in a 35-mile link.

Mid-beam	+65 db on 1 m^2
Quarter-point	+53 db on 1 m^2
Over station	+42 db on 1 m^2

In order to define our terms, these figures mean that at mid-beam the signal radiated by the aircraft to the receiver is 60 db greater than that intercepted by an area of 1 m^2 in the same field and radiated isotropically. The radar cross section of the Lancaster is approximately 60 m^2 or +18 db on 1 m^2.

<u>Receiver Sensitivity</u>:– The magnitude of the noise in a one-cps bandwidth of a receiver with a 10-db noise figure is –191 dbw referred to the input. The one-cps bandwidth is typical of the type of detection system used at present. The amount by which the signal must exceed noise depends upon the type of alarm or recording system used. It is probably safe to say that a signal of –170 dbw at the receiver input can be detected unequivocably, provided there is no external source of interference at the relevant low frequency corresponding to the high cross sections assumed. As will be seen later in discussing these long links, such interference is quite probable. However, the presentation of the echo strengths of an "ideal" system permits subsequent degrading of the figures on the basis of later information on such unknown factors as tower sway, atmospheric scintillation, etc.

<u>Reference Signal</u>:– Assuming the detection system in the receiver to be similar to those already used, the reference signal must exceed noise in the IF bandwidth at all

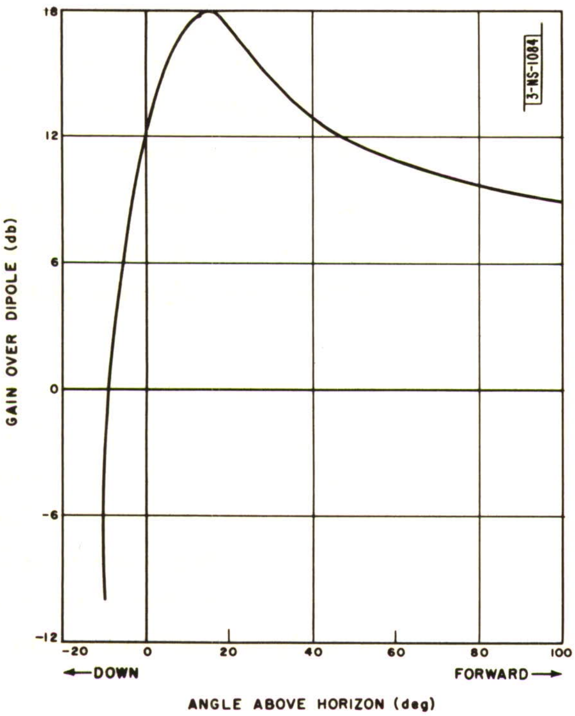


Fig.5A-3. Pattern of antenna assumed for calculations.

times. In the longer links, the reference signal is normally achieved by tropospheric scatter alone and is therefore likely to be relatively free from fading. It is probably adequate if it exceeds noise in the IF bandwidth by about 10 db.

It is assumed above that receiver noise in a 3-cps bandwidth is −186 dbw. If we decide that a 9-kcps IF bandwidth is feasible and consistent with high-grade crystal-oscillator stability, then the IF noise referred to in the input is 35 db above −186 dbw, i.e., −151 dbw. Under these circumstances, a reference signal of −140 dbw is adequate.

Antenna:– The antenna assumed in these calculations has the polar diagram in the forward 90° shown in Fig. 5A-3. It has a gain of 20 db in the main lobes and resembles in vertical pattern the "ideal" antenna specified for the RCA Victor Fluttar development, but has about 6 db greater gain achieved, for instance, by doubling the linear dimensions (8 × 10 feet to 16 × 20 feet).

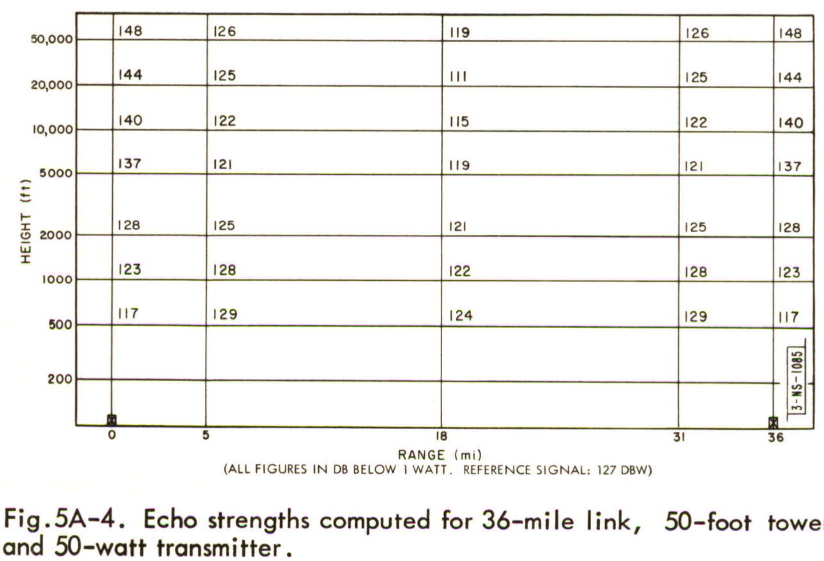


Fig.5A-4. Echo strengths computed for 36-mile link, 50-foot towers and 50-watt transmitter.

Discussion of Several Links

Echo strengths for the following links have been presented on an axial section of the link using a linear scale of distance and a logarithmic scale of height. This gives emphasis to any failure of low cover which might not otherwise be apparent.

<u>35-Mile Link with 50-Foot Towers, 50-Watt Transmitter</u>:– For comparison, the echo strengths computed for a 36-mile link are included in Fig. 5A-4. They represent a fair average value of the echoes actually measured in two experimental links using a Lancaster aircraft.

<u>75-Mile Link with 150-Foot Towers, 50-Watt Transmitter</u>:– Figure 5A-5 shows the echoes computed for a 75-mile link with a 150-foot tower at each end, using a 50-watt transmitter. The low cover is inclined to be weak, particularly at the quarter-points. The area covered by line-of-sight transmission and reception is well covered. The magnitude of the reference signal is very low and it is doubtful whether a working link could be made with this tower height. Raising the tower height to 300 feet would barely alleviate this problem. To summarize, the reference signal "goes out" before the aircraft cover.

<u>100-Mile Link with 300-Foot Towers, 10-kw Transmitter</u>:– Figure 5A-6 shows the echoes computed for a 100-mile link with 300-foot towers. This and the subsequent diagrams have been computed for a 10-kw transmitter. Correction can be made for lower powers by subtracting the number of db below 10 kw from the figures given.

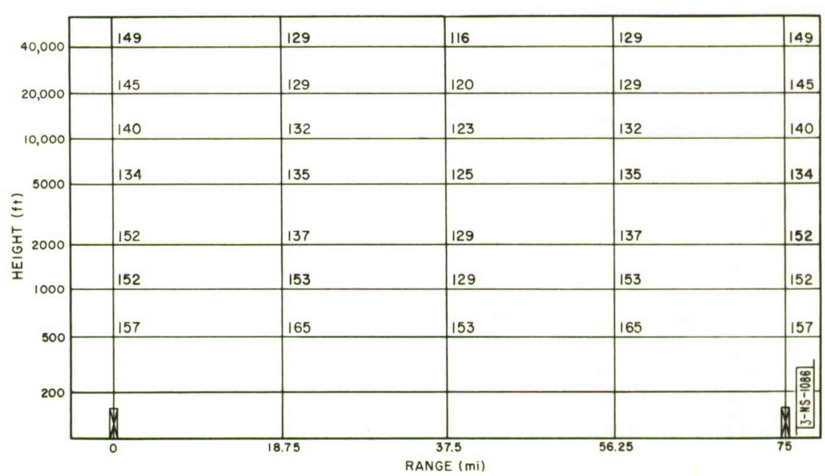


Fig.5A-5. Echo strengths computed for 75-mile link, 150-foot towers and 50-watt transmitter (smooth earth).

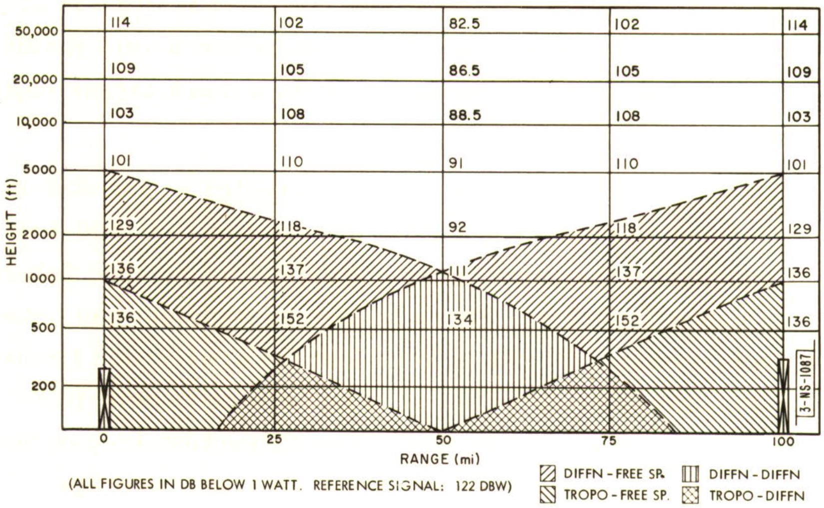


Fig.5A-6. Echo strengths computed for 100-mile link, 300-foot towers and 10-kw transmitter (smooth earth).

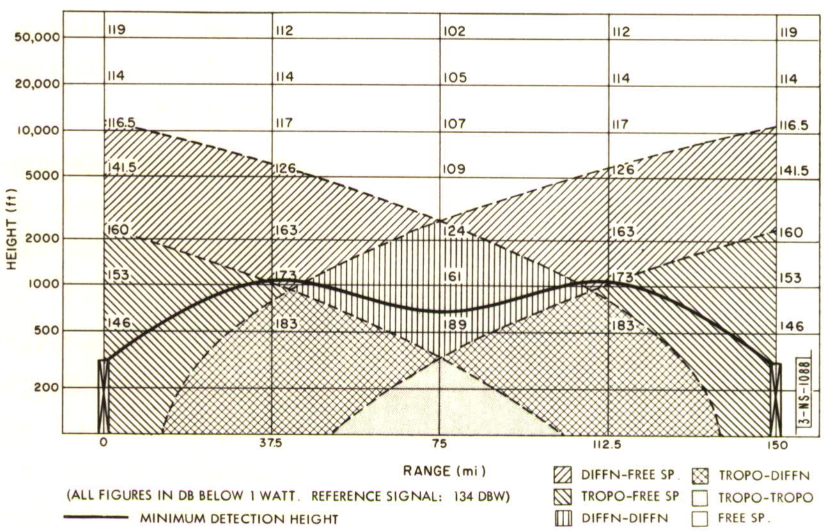


Fig.5A-7. Echo strengths computed for 150-mile link, 300-foot towers and 10-kw transmitter (smooth earth).

The coverage everywhere is excellent in this link. However, one of the faults of high-power links is apparent. The signal high in the center of the link is at least 60 db higher than that necessary for detection. This means that a very small moving object in this location could cause an echo comparable with a much larger object in a less favorable location.

150-Mile Link with 300-Foot Towers, 10-kw Transmitter:– The 150-mile link (Fig. 5A-7) has stretched the distance just beyond the limit for 300-foot towers on smooth earth. Coverage in the center does not extend below 1000 feet and at the quarter-points not below 2000 feet. There is also an incipient gap between 1000 and 3000 feet above each station. It will be seen that the area within tropospheric scatter from each station (assuming reciprocity) is of no service to detection. This also applies to the lower diffraction regions and to the diffraction-tropospheric regions. In general, the free-space-diffraction regions show adequate coverage.

200-Mile Link with 300-Foot Towers, 10-kw Transmitter:– This is a worse case of the above to which the same remarks apply (Fig. 5A-8).

200-Mile Link with 5000-Foot Sites, 10-kw Transmitter:– Figure 5A-9 shows the effect of raising both sites to 5000 feet. Perfect coverage is achieved, although the low cover at the quarter-points has very little in hand. At this distance with 10 kw power the diffraction-diffraction region gives excellent cover.

200-Mile Link with 300-Foot Tower One End, 5000-Foot Site the Other:– Figure 5A-10 illustrates the effect of raising only one end. As might be expected, there is very poor low cover toward the higher site, due to the fact that this region is only in tropospheric scatter contact with the remote (lower) station.

300-Mile Link with 5000-Foot Sites, 10-kw Transmitter:– Figure 5A-11 shows the effect of extending the range further and should be compared with Fig. 5A-9 for the 200-mile link. The extension of range has a devastating effect both on low cover (below 10,000 feet!) and over the station. Again, tropospheric scatter is no help at all to the aircraft response and at this range any appreciable penetration into the diffraction region reduces the signal below the useful level.

Doppler Frequencies

We have so far considered only the amplitude of the Doppler aircraft signal at a limited number of points in typical links. The computations were made using the most favorable values for the aircraft cross section, i.e., those corresponding to a location close to the axis of the link and a frequency of about one cps for normal aircraft speed.

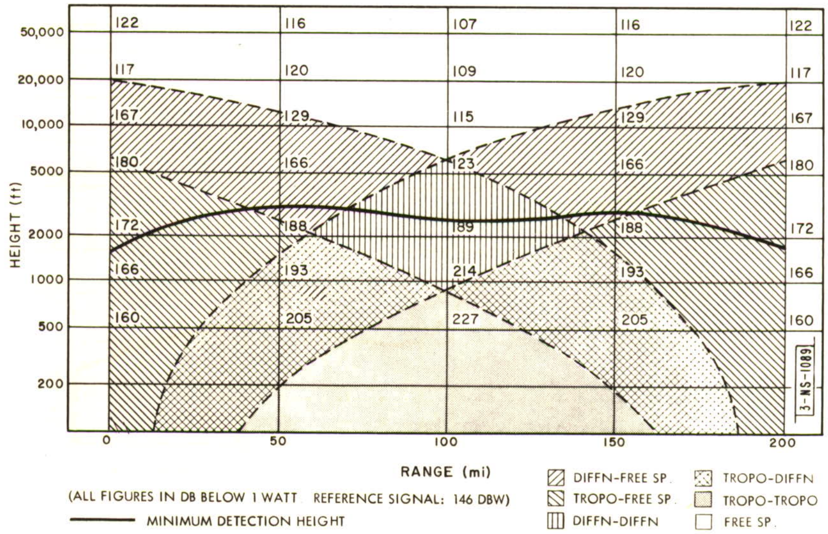


Fig.5A-8. Echo strengths computed for 200-mile link, 300-foot towers and 10-kw transmitter (smooth earth).

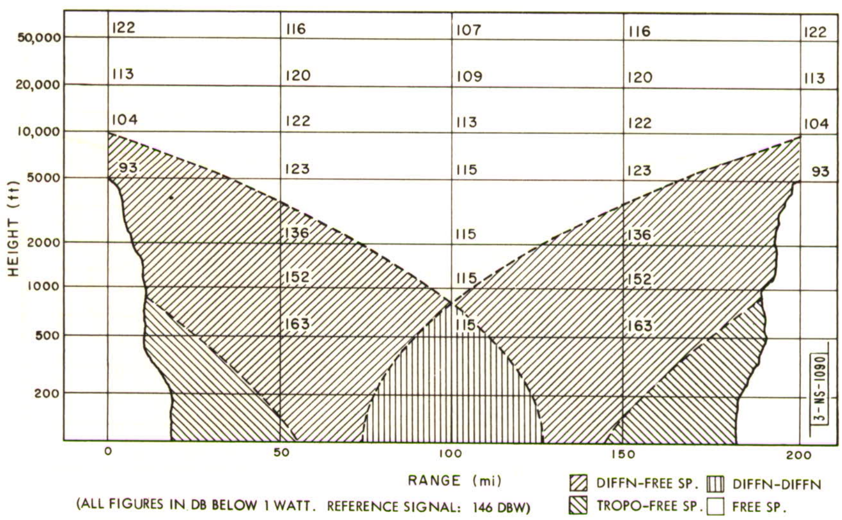


Fig.5A-9. Echo strengths computed for 200-mile link, 5000-foot sites and 10-kw transmitter (smooth earth).

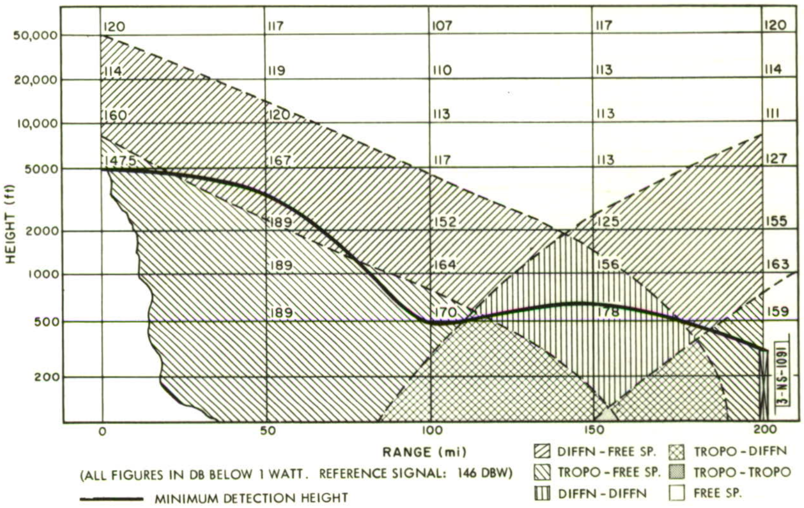


Fig. 5A-10. Echo strengths computed for 200-mile link, 5000- and 300-foot sites and 10-kw transmitter (smooth earth).

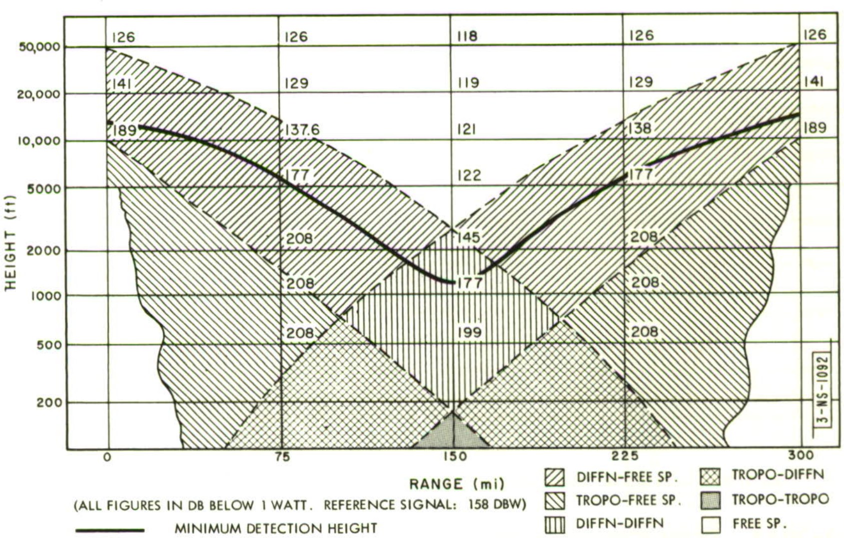


Fig. 5A-11. Echo strengths computed for 300-mile link, 5000-foot sites and 10-kw transmitter (smooth earth).

The Doppler frequency produced by a target at a given distance from the axis of the link midway between the two stations is inversely proportional to the length of the link. Thus the longer links, although producing the same total range of Doppler frequencies, will produce lower frequencies in some locations. This may increase the difficulty of taking advantage of the high effective cross section of an aircraft near the axis of the link.

Interfering Signals

The main sources of interfering signals in any link are:

> Transmitter modulation due to tower sway,
>
> Atmospheric "scintillations" or very fast low-level fluctuation of the transmission-path attenuation,
>
> Man-made interference,
>
> Small moving objects such as birds.

There is some evidence at present that the received noise below 10 cps may be increased above the noise inherent in the receiver by as much as 30 db. The precise reason has not been established, but it is thought that at least some of this noise arises from fluctuations in the attenuation path or from Doppler reflections from thermal air currents.

It will be observed that some of the links using a high-powered transmitter exhibit a very wide variation in the intensity of echoes as a function of the location of the target. In order to detect an aircraft in a poorly covered location, it is necessary to maintain the system sensitive to a signal some 60 db smaller arising at another location in the link. This may well increase the susceptibility of the system to noise of the variety ascribed to thermal air currents or to the detection of large birds. It may be significant that the only confirmed signals from birds have been obtained on the Lincoln Laboratory long-range experiments.

The use of high towers makes it increasingly difficult to achieve the angular stability necessary to avoid modulation due to vibration of either antenna. The order of stability required is $\pm 1/10°$ for the simple McGill fence system.

Man-made interference cannot be discussed in this report.

Conclusions

The following conclusions may be drawn from the above data.

> Over smooth earth, a 100-mile link with 300-foot sites using a 10-kw transmitter and the best receiving system available

should be feasible in that an adequate reference signal and excellent echo amplitudes are realized. This neglects a detailed consideration of atmospheric fluctuations, detection of birds and tower sway.

Under similar conditions and with a similar proviso, a link of 150 to 175 miles with 5000-foot sites is feasible. The 200-mile link of Fig. 5A-9 is just beyond the maximum range for this height.

There is no advantage to be gained by raising the site at one end of a link over smooth earth excessively beyond the height of the other site (Fig. 5A-10).

The reference signal is adequate on all but the 300-mile link with 10 kw of transmitted power. The 300-mile link would require about 18 db increase in either antenna gain or transmitted power to achieve an adequate reference signal. These figures are relatively independent of tower height if the tropospheric-scatter data are reliable.

Tropospheric scatter makes possible the establishment of links at long range by providing a reference signal at points where the diffracted signal is vanishingly small. It is evident from the curves, however, that tropospheric-scatter propagation helps the system coverage little or not at all. In fact, it is necessary to have all points of the system at which coverage is required either in the free-space region or in the upper diffraction region from both sites. The curves of Fig. 5A-11 provide a graphic demonstration of this fact.

Recommendations

Further data are required on the following items which are regarded as important.

Further experimental information on tropospheric scatter. This is being gathered at a number of locations in the United States.

The synthesis of a number of links with simple obstacles in them. The obstacle gain produced may be embarrassing in providing an excessive reference signal, and the masking effect may reduce low cover at some points.

Further information on aircraft cross sections in the system, and particularly on their variation with distance from the axis at various locations in the link. This will be obtained by a detailed analysis of the data resulting from the summer (1954) tests in Montreal by Whitehead. It could well be supplemented by model work at millimeter wavelengths. The recent data which have arisen from the summer tests tend to show that the forward scatter would be easier (and therefore more accurate) to measure by several orders of magnitude than the radar backscatter cross section and, also, that it would be less dependent on minor variations between the model structure and that of the large aircraft.

A study of the sources of "scintillation" noise at low frequencies, which is the greatest limitation of the system at present.

Experimental data on a long link in the field to check the accuracy of the foregoing. This should be on the lines of the summer tests which produced reliable reproducible data that have been extrapolated for use as a basis for the above computations.

Introduction

100 MEGACYCLES

The data of this section supplement the information of the first section. The previous results relate to a frequency of 500 Mcps horizontally polarized over land or sea or vertically polarized over land. They also apply approximately to the same frequency vertically polarized over sea.

The new computations relate to a frequency of 100 Mcps vertically polarized over sea. The examples taken (Figs. 5A-14 to 5A-17) correspond to those given previously for a frequency of 500 Mcps.

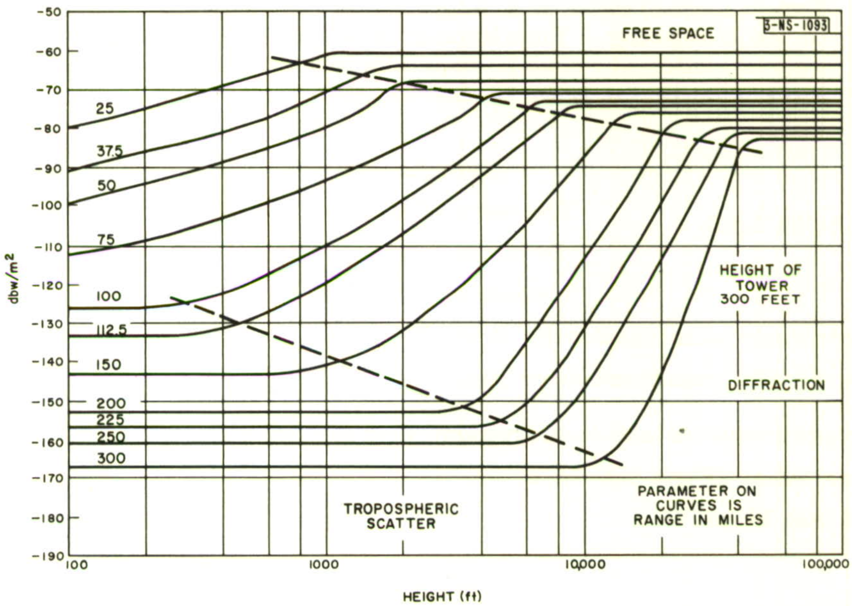
Assumptions

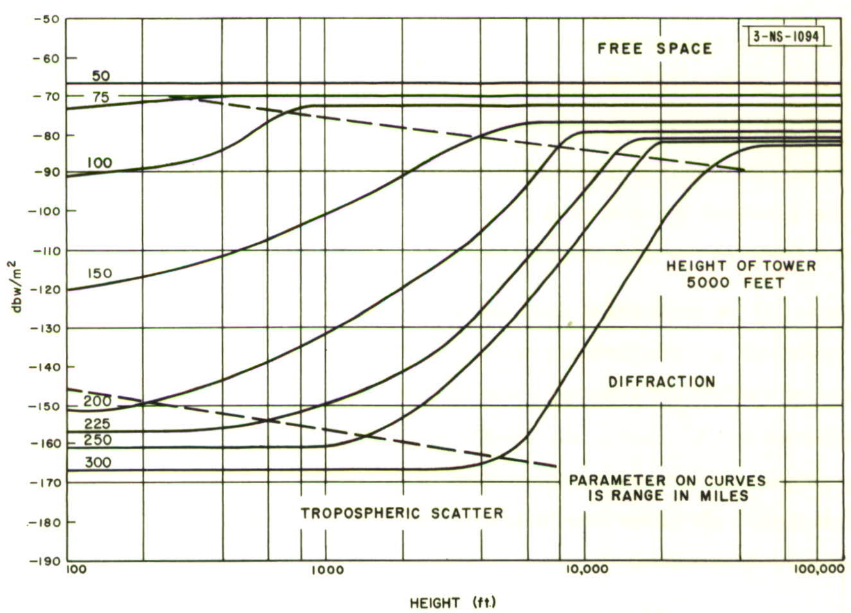
The assumptions made are the same as those in the previous examples, with the following exceptions.

Antenna Gain:– For the purpose of computing the following diagrams, the "ideal" antenna diagram of Fig. 5A-3 has been assumed to hold at 100 Mcps with the same antenna gain of 20 db over an isotropic radiator. This corresponds to an antenna roughly 100 × 70 feet and is probably an unreasonable assumption. However, a correction for the amount by which a practical antenna falls short of this may be made directly to the figures on the diagrams.

Cross Section:– It is probable that the cross section of an aircraft on the axis of the link will be reduced as the frequency is lowered. If all the energy arises from a highly directive lobe of reflected energy, as is now believed, the effective cross section should be reduced by λ^2, i.e., by 14 db in going from 500 to 100 Mcps. In the diagrams on the facing page, the cross section has been reduced (over that at 500 Mcps) by only 8 db within the link and 6 db over the station, which is considered optimistic. The cross sections used are therefore

Mid-link	57 db above 1 m^2
Quarter-point	45 db above 1 m^2
Over station	37 db above 1 m^2


3-NS-1093
FREE SPACE
25
37.5
50
75
100
112.5
150
200
225
250
300
HEIGHT OF TOWER 300 FEET
DIFFRACTION
PARAMETER ON CURVES IS RANGE IN MILES
TROPOSPHERIC SCATTER
dbw/m²
HEIGHT (ft)
100
1000
10,000
100,000
-50
-60
-70
-80
-90
-100
-110
-120
-130
-140
-150
-160
-170
-180
-190


3-NS-1094
FREE SPACE
50
75
100
150
200
225
250
300
HEIGHT OF TOWER 5000 FEET
DIFFRACTION
PARAMETER ON CURVES IS RANGE IN MILES
TROPOSPHERIC SCATTER
dbw/m²
HEIGHT (ft)
100
1000
10,000
100,000
-50
-60
-70
-80
-90
-100
-110
-120
-130
-140
-150
-160
-170
-180
-190

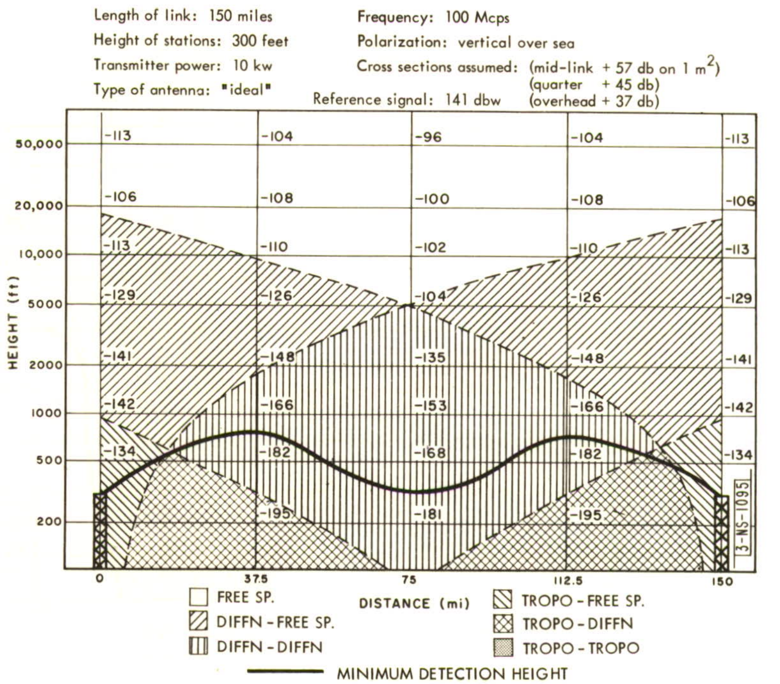


Fig.5A-14. Echo strengths computed for 150-mile link, 300-foot towers and 10-kw transmitter.

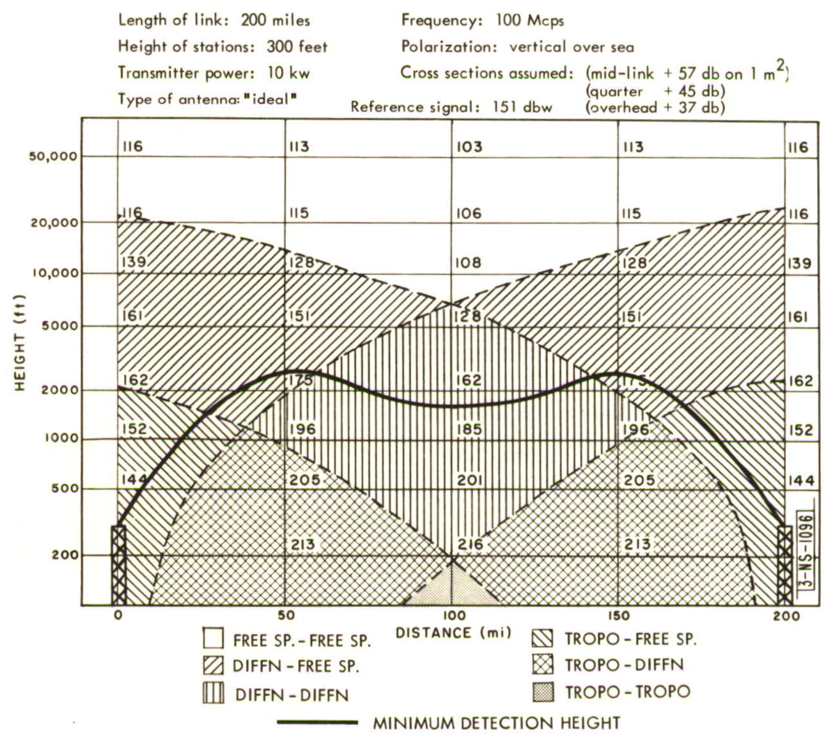


Fig.5A-15. Echo strengths computed for 200-mile link, 300-foot towers and 10-kw transmitter.

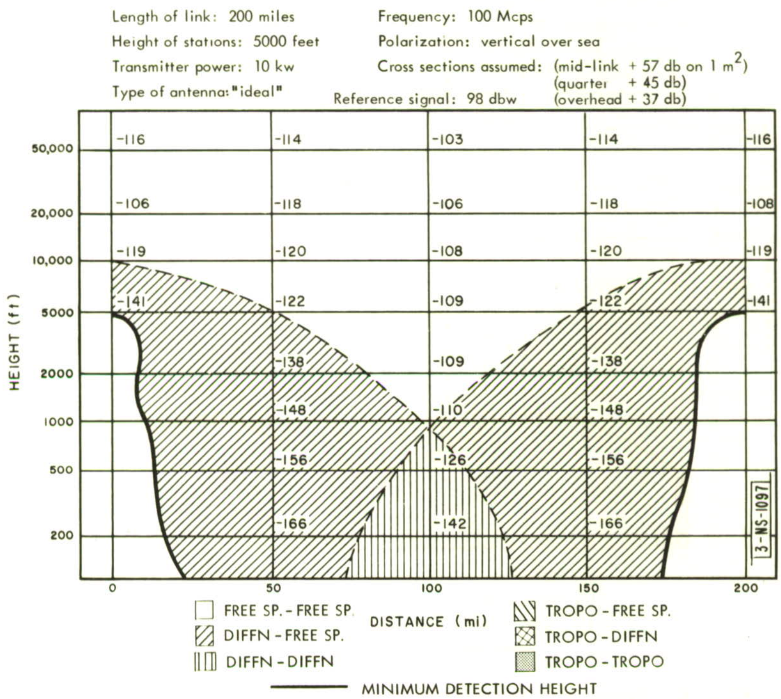


Fig.5A-16. Echo strengths computed for 200-mile link, 5000-foot sites and 10-kw transmitter.

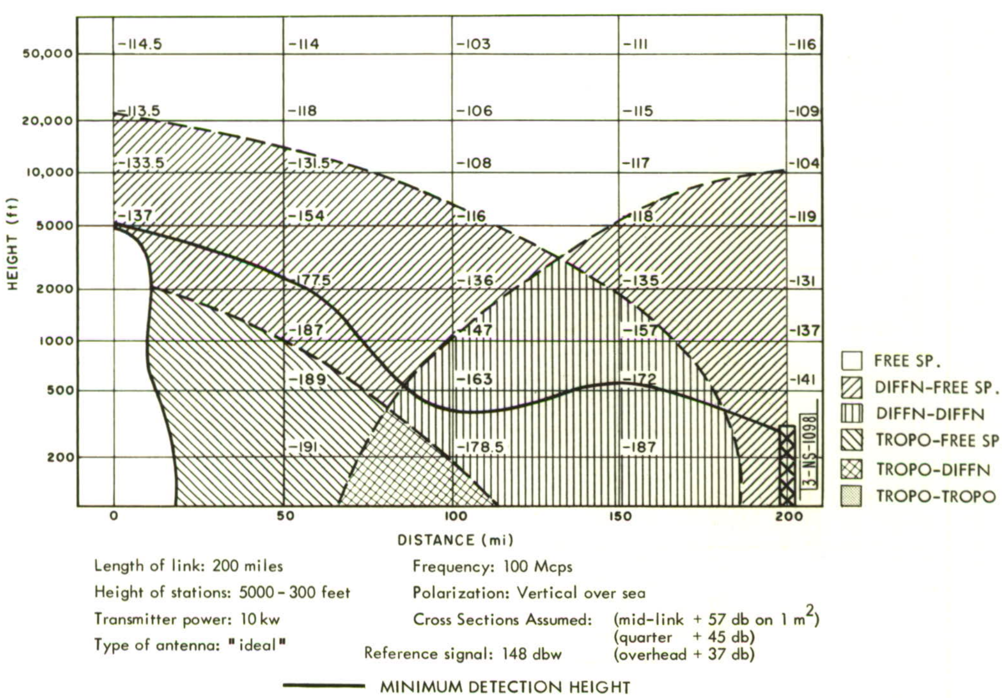


Fig.5A-17. Echo strengths computed for 200-mile link, 5000- and 300-foot sites, and 10-kw transmitter.

These correspond to a Lancaster aircraft, but the figures for a B-36 would differ only by about 6 db.

Discussion

Figures 5A-14, 5A-15, 5A-16 and 5A-17 show four synthetic links comparable with the previous Figs. 5A-7, 5A-8, 5A-9 and 5A-10, respectively. The diffraction region, as expected, spreads both upward and downward at the lower frequency, and tropospheric scatter has less importance. This has the effect of improving the cover in the borderline region, but does remarkably little to change an impossible link to a feasible one.

Doppler Frequencies

The Doppler frequencies on a 100-Mcps link would be scaled down by a factor of five due to frequency over those on a 500-Mcps link. This, coupled with the reduction due to the length of the link, means that an aircraft crossing at mid-link at right angles would produce no frequency in the beam higher than about 2 cps, if that. This, in itself, is probably prohibitive against such a reduction of frequency.

Tentative Conclusions

Even with the optimistic assumptions made with regard to antenna gain and cross section, a 100-Mcps link shows only moderate improvement in low cover over a 500-Mcps link. A more realistic estimate of the above parameters would reduce the values of signal strength in Figs. 5A-14, 5A-15, 5A-16 and 5A-17 by 12 to 15 db.

The reduction of Doppler frequency would make detection considerably more difficult.

As a result, it is probable that a practical 100-Mcps link at a given distance would not perform as well as a link at 500-Mcps with slightly increased tower height.

A reduction of frequency from 500 to 100 Mcps would improve a situation in which low cover was marginal at 500 Mcps and no change in site or tower height was feasible. This is an unlikely situation.

Experiments made in the auroral zone show that aurora reflect frequencies up to 200 Mcps. Doppler alarms produced by moving aurora may prove troublesome at 100 Mcps.

J. R. Whitehead
J.C.W. Scott

APPENDIX 5-B

TARGET LOOP REGENERATION

In Fluttar detection systems, energy is propagated from transmitter to receiver over two separate paths. The Doppler-shifted signal is transmitted via the target and the reference carrier is transmitted directly over the curved earth. Propagation conditions can thus produce large variations in reference amplitude independently of the target signal level.

This places limits on the spacing between transmitter and receiver. On the one hand, a sufficient reference signal must always be available for Doppler detection and on the other, the reference must not rise so many magnitudes above the target signal that small fluctuations upon it are comparable to the Doppler amplitude.

Again, in Fluttar systems the Doppler frequency is determined by the rate at which the target cuts the ellipsoids of constant path length between transmitter and receiver. The Doppler frequency is proportional to the carrier frequency and is given by $d = 1/\lambda \, (d\ell/dt)$, where λ is the wavelength and ℓ the distance from transmitter to receiver via the target.

The width of the noise spectrum, due to variations of propagation, increases linearly with the carrier frequency and has maximum amplitude at the lowest audio frequencies. Thus, at low target speeds or for directions and regions of crossing giving low values of $d\ell/dt$, the Doppler frequency may be in the band of significant fluctuation noise on the reference signal.

All these limitations are the result of requiring two separately propagated signals. If the reference signal could be eliminated, these limitations would be relaxed. The most direct method of eliminating the requirement for a reference signal is to use stable oscillators. In order to prevent false alarms from beats in the Doppler range above one cps, using a transmission frequency of 500 Mcps, a stability of better than one part in 500 million would be required. An alternative system requiring far lower stability is outlined below.

The proposed system uses a transmitter and receiver at each end of the path. Energy is transmitted from one end to the other only via the target. It is returned at a slightly different frequency by the same means. The antennas are beamed so that little energy is passed in the absence of a target but when a target is present a closed loop is formed, allowing the system to oscillate.

At each end the received energy is amplified, shifted slightly in frequency, again amplified and re-radiated. The amplifier gain at each terminal is set so as to be just

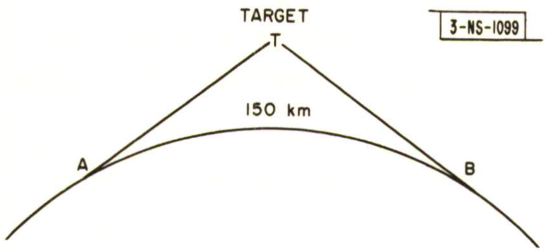


Fig. 5B-1. Geometry of transmission path.

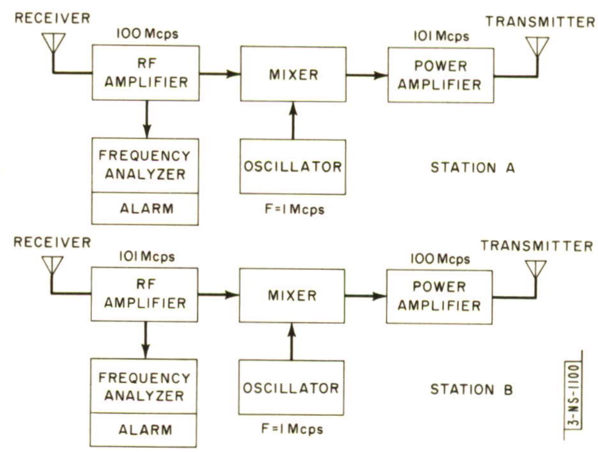


Fig. 5B-2. Block diagram of proposed Fluttar system.

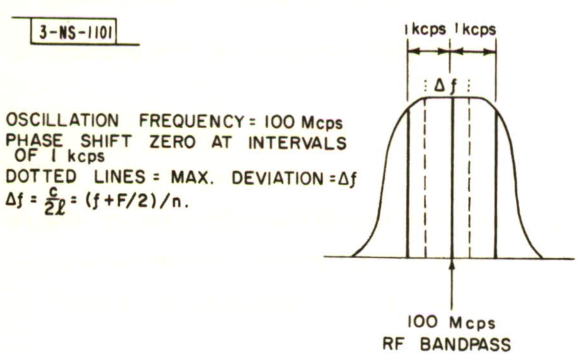


Fig. 5B-3. Oscillation frequency for fixed target.

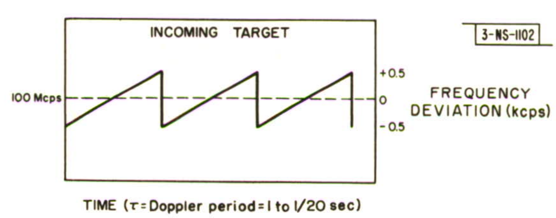


Fig. 5B-4. Saw-tooth frequency variation for an incoming target.

above the maximum transmission-path loss for the detection of targets of given minimum cross section. Under these conditions the system will oscillate at frequencies for which the phase shift around the loop is zero and the gain is maximum. Limitation is used to prevent saturation on large signals.

The geometry of the path is shown in Fig. 5B-1, and an elementary block diagram in Fig. 5B-2. When a target T raises the loop gain above one, the loop oscillates at frequencies f and f + F determined by the condition that the loop phase shift is zero. Here F is the fixed frequency of the oscillators in the two terminals. If C is the velocity of light and n is an integer equal to the total number of wavelengths in the loop length 2ℓ, then the frequencies of oscillation are determined by the relation,

$$f = \frac{C}{2}\frac{n}{\ell} - F/2 \quad . \tag{1}$$

A change in the frequency of oscillation is subject to the condition

$$df = (f + F/2)\left(\frac{dn}{n} - \frac{d\ell}{\ell}\right) \quad . \tag{2}$$

Consequently, if the target is fixed, oscillation could occur at frequency intervals of

$$df = (f + F/2)/n \quad , \tag{3}$$

as shown in Fig. 5B-3. However, oscillation will occur where the gain is maximum.

If the target moves so as to cut the ellipsoids of constant path length, the frequency of oscillation will shift as determined by

$$- df = (f + F/2)\, d\ell/\ell \quad , \tag{4}$$

when $d\ell = \ell/n$, the frequency deviation is maximum and the oscillation frequency snaps back to f. The deviation is repeated as the target moves, at a repetition frequency equal to the Doppler frequency for the average of the two carrier frequencies f and f + F.

The repetition frequency is thus

$$d = (f + F/2)\,/c\,(d\ell/dt) \quad . \tag{5}$$

Moreover, the deviation is positive for incoming targets and negative for outgoing targets. Figure 5B-4 illustrates the saw-tooth frequency variation for an incoming target. The maximum deviation is also given by

$$df = c/2\ell \quad , \tag{6}$$

so that the maximum deviation determines the position of the target as on a given ellipsoid defined by ℓ.

The sensitivity of the system appears to be limited only by the gain of the amplifiers at each terminal. By using antennas with a null on the direct path between stations 40 db down on the lobe maximum, false alarms due to direct-path oscillation could not occur unless anomalous propagation raised the received signal 80 db. It is also possible that by limiting the gain on large signals, targets could be seen through the fixed direct-path signal.

If the amplifier gain were set so that noise peaks at the receiver input were limited, the gain would be reduced during these peaks. Oscillation would still build up while the loop gain was greater than one between noise peaks. Qualitatively, it would seem that whenever the integrated loop gain were greater than one the target would be detected.

The proposed system should be further analysed and tested experimentally.

J.C.W. Scott

APPENDIX 5-C
PULSED FLUTTAR

To eliminate false alarms caused by variations of the Fluttar reference signal, the following pulsed Fluttar system is proposed. Briefly, the Fluttar transmitter is pulsed on for a duration which is so short that desired signals coming from targets off the axis arrive after the directly received pulse has terminated. Signals arriving after this time are thus completely separated from the direct signal which, due to fluctuations in its intensity, is a cause of false alarms.

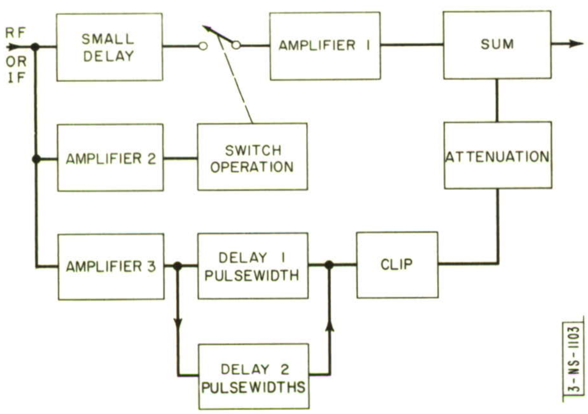


Fig.5C-1. Block diagram of proposed pulsed Fluttar system.

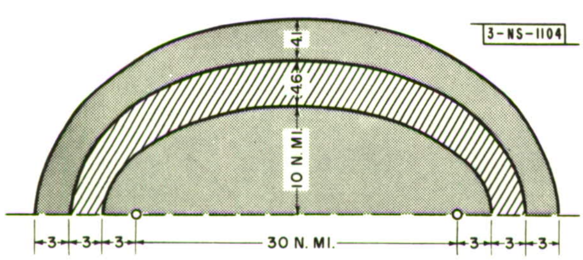


Fig.5C-2. Proposed "dome" for 30-mile station separation.

Figure 5C-1 blocks out roughly the essentials of the modification. The signal (at RF or IF) is fed to Amplifier 2 and detected, the direct high-level signal being used to operate a switch that keeps Amplifier 1 input disconnected during the pulse duration. A slight delay is inserted before the switch to make sure that no main bang gets into Amplifier 1 before the switch can operate. After the main bang, the switch is closed, and target signals are fed through Amplifier 1. The main bang is also fed through Amplifier 3, delayed one pulsewidth, clipped to remove amplitude fluctuations, attenuated and added to the target signals from Amplifier 1 to provide the desired Doppler. In order to provide a wider region of activity, the main bang may be extended by also delaying it two pulsewidths and adding. Operation from here on is identical to the present system.

The device has the effect of making the "fence" consist not of a solid set of ellipsoids, but of a hollow shell, whose cross section in any plane through the axis is shown in Fig. 5C-2. The cross-hatched area is completely active, i.e., any target in this area will give a pulse that arrives at the output of the device entirely within the interval when the delayed reference signals are on. In the dotted area, the sensitivity falls off linearly to zero along the baseline and at the outer ellipsoid, since the target pulse will fall partially outside the reference-

signal interval in these circumstances. The boundaries of the shells are determined by the surfaces of constant arrival-time delay equal to zero – one, two and three pulse-lengths, respectively. The desired shape of this area determines the pulsewidth.

For a 30-mile station separation, a "dome" such as that shown in Fig. 5C-2 might be desirable; this gives solid altitude coverage above the station to 50,000 feet, falling off to zero signal at 75,000 feet. For this geometry the minimum path difference is 6 miles, giving a pulsewidth of 32 μsec. A duty cycle of 1/10 should be ample to avoid "second-time-around" effects, if this is desirable. A duty cycle of 1/3 would give a set of shells, alternating completely active and graded activity. A much shorter pulse operating at a high duty cycle could give essentially the same coverage as at present. It is evident that a wide variety of structures could be obtained by varying the amount and number of delays. A region of zero sensitivity around the baseline (instead of partial sensitivity) can be obtained by an initial delay of more than one pulsewidth.

The proposed system has the following advantages:

> False-alarming due to amplitude variation of the reference signal is eliminated.
>
> The target signal is being compared with a transmitted signal which was generated somewhat closer in time to the former (this may help on transmitter noise).
>
> No effort need be made to keep the strength of the direct signal at low values.
>
> Because of the insensitive region extending back of the antenna, some relief from false-alarming due to cars and birds may be obtained.

The equipment necessary to do this job is quite ordinary. Some increase in transmitter power might be desirable to make up for the target's being in the beam for a shorter time; for a short-pulse multi-shell scheme, this need not exceed 3 times the present power.

J.W. Coltman

APPENDIX 5-D

PREDICTED PERFORMANCE OF VELOCITY-DISCRIMINATING FLUTTAR SYSTEMS*

INTRODUCTION

The various types of Fluttar systems have been studied intensively at Lincoln Laboratory because of the need for a bistatic detection system to complement the low-altitude coverage of the scanning radars in the DEW line. The objective of these studies has been to determine system parameters suitable for use in sites having baselines varying from 40 to 70 miles. A number of the proposed DEW sites are known to be situated in areas frequented by a large bird population during the summer months. Since field tests have indicated that single birds will be detected on a 50-mile baseline system, discrimination on an amplitude basis did not appear practical for the intended application. Consequently, considerable effort has been placed on the development of a system that will provide for discrimination on a velocity basis, thereby separating slowly moving birds and the echoes from aircraft which have a higher velocity. Although there is insufficient experimental information to conclude that the proposed system will be completely bird-free, it is believed that the number of false alarms produced by flocks of birds can be kept to a level manageable at a DEW site.

DISCUSSION

The principal difference between the on-baseline and off-baseline fence systems is in the basic method employed for detecting aircraft targets. The on-baseline system primarily utilizes amplitude information, while the off-baseline system utilizes velocity discrimination. In the velocity-discrimination system the transmitter and receiver antennas do not point at each other – rather, each one has a horizontal offset of 15° from the line (baseline) joining the transmitter and the receiver.

When a target enters the system, it intercepts some of the transmitted energy and re-radiates a portion thereof. Because of the Doppler effect, the energy reflected by the airplane has a frequency that is slightly different from the transmitter frequency. This small difference in frequency, which is detected by a sensitive receiver, constitutes the Fluttar signal.

A significant feature provides "sense" information; i.e., indicates whether the target crossing is from north-south or south-north. For certain special courses the Fluttar

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*A more complete discussion of this system is given in Lincoln Laboratory Group Report 31-119.

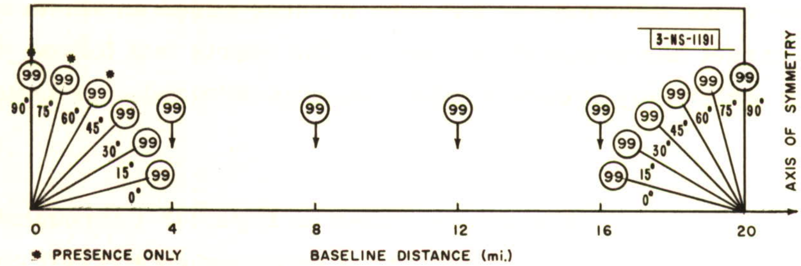

Fig.5D-1. Probability of detection for 40-mile baseline.

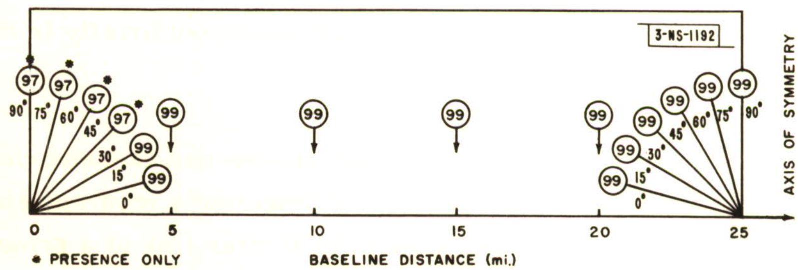

Fig.5D-2. Probability of detection for 50-mile baseline.

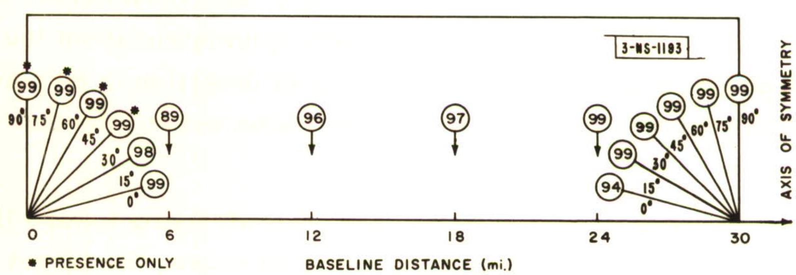

Fig.5D-3. Probability of detection for 60-mile baseline.

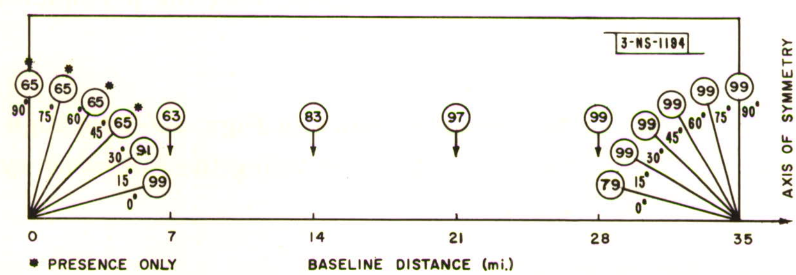

Fig.5D-4. Probability of detection for 70-mile baseline.

link does not give sense information, but even in these cases an alarm is obtained indicating that a target has crossed the line. In the charts that follow, these particular courses, for which only presence information is obtained, are indicated with an asterisk.

PROBABILITY OF DETECTION CHARTS

The charts shown as Figs. 5D-1 through 5D-4 present the probability of detecting an aircraft comparable to the B-47 crossing a Fluttar line at an altitude of 200 feet with a ground speed of 200 knots. These data are given for transmitter-receiver separations of 40, 50, 60 and 70 miles. The assumptions used in arriving at these results are presented briefly in the last section of this Appendix.

USE OF CHARTS

In order to illustrate the use of these charts, consider the probability of detecting a medium-sized target that crosses a 50-mile Fluttar link at a ground speed of 200 knots at an altitude of 200 feet. Assume further that its straight-line course is normal to the baseline, 10 miles from the receiver. (If the crossing were 10 miles from the transmitter, the probability of detection would be the same because the Fluttar link is completely symmetric about the middle of the baseline.) According to Fig. 5D-2, the probability of detection is 99 per cent. Since no asterisk is shown for this course, the system yields sense information as well as presence information.

As a second example, consider a medium-sized aircraft flying toward the transmitter at an angle of 75° to the baseline. The baseline is 60 miles, the target speed is 200 knots, and the airplane altitude is 200 feet. From Fig. 5D-3, the probability of detection is 99 per cent. Since this trajectory has an asterisk, the Fluttar link does not determine the direction of crossing in this case; only the presence of an aircraft is indicated.

PARAMETERS

The results shown in Figs. 5D-1 through 5D-4 have been calculated utilizing the following system parameters.

Transmitter power: 1.0 kw.

Transmitter frequency: 500 Mcps.

The propagation data used were calculated by standard methods. The amount of fading considered is believed to yield a very conservative estimate of the probability of detection.

Target cross section: 12 m^2.

Transmitting and receiving antennas are the same. Each is offset from the baseline by 15°; each has a horizontal beamwidth of 20° and a gain of 23 db.

For all baselines, except the 70-mile case, the antennas are connected to the appropriate equipment with 1-5/8-inch coaxial cable equal in length to twice the tower height. The losses for this cable are 0.34 db per 100 feet. For the 70-mile baseline where taller towers are necessary, aluminum waveguide with a loss of only 0.07 db per 100 feet is used in place of coaxial cable.

False-alarm rate: approximately 1 per two weeks.

H.G. Weiss
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DEPARTMENT OF THE AIR FORCE
WASHINGTON, DC

3 September 2008

HAF/IMII (MDR)
1000 Air Force Pentagon
Washington, DC 20330-1000

Department of the Navy
Naval Research Laboratory
ATTN: Vicki L. Cicala
4555 Overlook Avenue SW
Washington, DC 20375-5320

Dear Ms. Cicala

Your letter dated 9 January 2008, requesting a Mandatory Declassification Review of the following documents:

S30921 Final Report of Project Lamp Light, Vol I DTIC AD0311318
S30922 Final report of Project Lamp Light, Vol II DTIC AD0311319
S30923 Final Report of Project Lamp light, Vol III DTIC AD0311320
S30924 Final Report of Project Lamp Light, Vol IV DTIC AD0311321

The appropriate Air Force agency has reviewed the documents IAW the Executive Order 12958, as amended, and finds we have no objection to the declassification and release of the Air Force information.

Address any questions concerning this review to the undersigned at DSN 223-2560 or COMM (703) 693-2560 and refer to case number 08-MDR-040.

Sincerely

Joanne McLean

JOANNE MCLEAN
Mandatory Declassification Review Manager

1 Atch
Documents for Review (S)

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